Ocean: #1
Introduction

Why do we study ocean?

- It is interesting in its own right.
- It plays an important role in climate and climate variability.
    - Abrupt climate change
- The air we breathe
    - The ocean produces over half of the world's oxygen and absorbed 50 time more carbon dioxide than the atmosphere

How is the ocean different from the atmosphere?

Difference #1: Type of the fluid

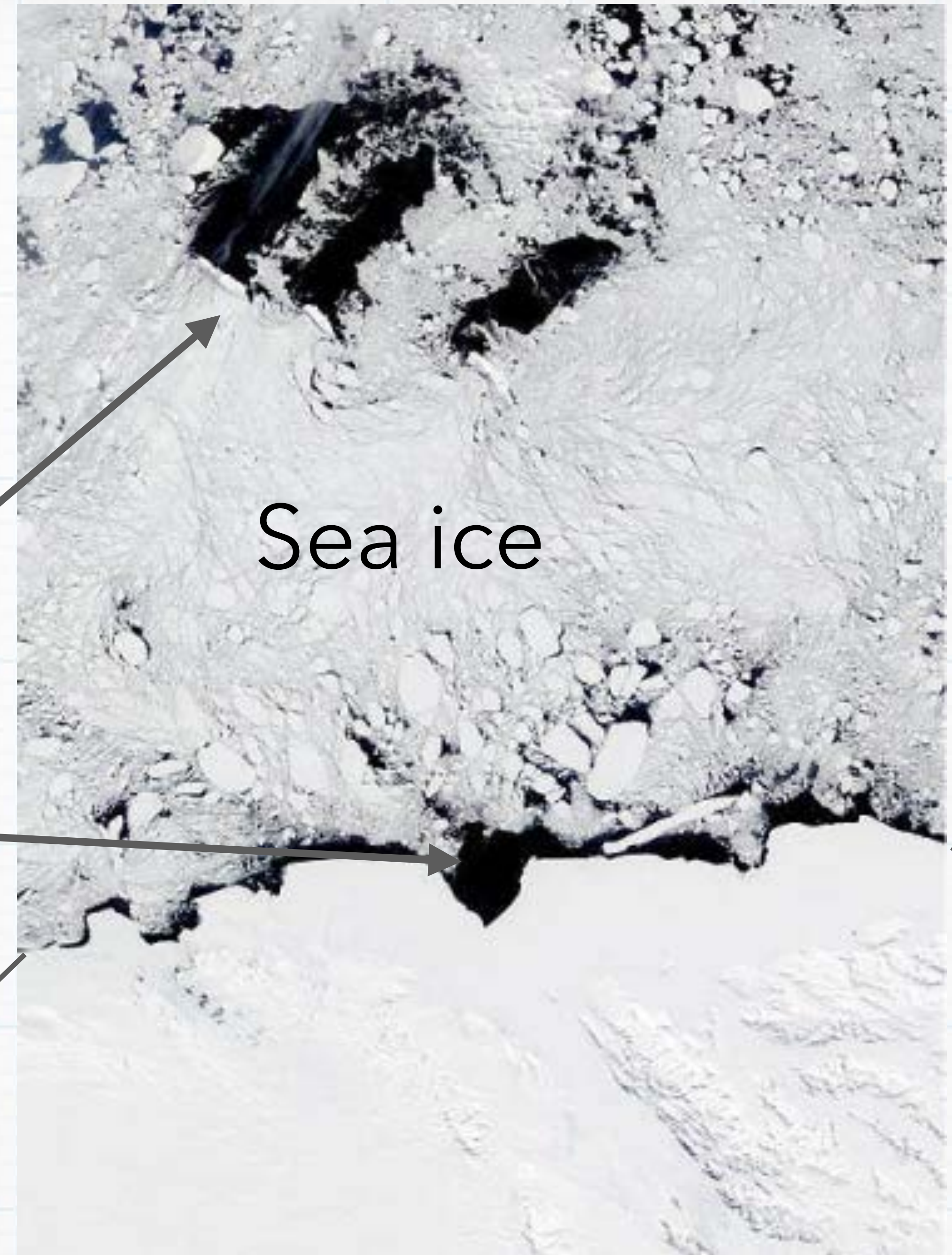
- Atmosphere = air : Compressible fluid
- Ocean = water : Nearly incompressible
- Internal energy can go up or down in the compressible fluid (like air) by changing the volume.
- Internal energy can go up or down in the incompressible fluid (like water) by heating or cooling it.

It is interesting to note that if seawater were really incompressible, sea level would be about 50 m higher than it is.

Difference #2: Latent heat

- The atmosphere has moisture.
  - Moisture can be a source of latent heat.
- The ocean does not have counterpart to atmospheric moisture.
  - (Well, latent heat can be release when sea-ice forms.)

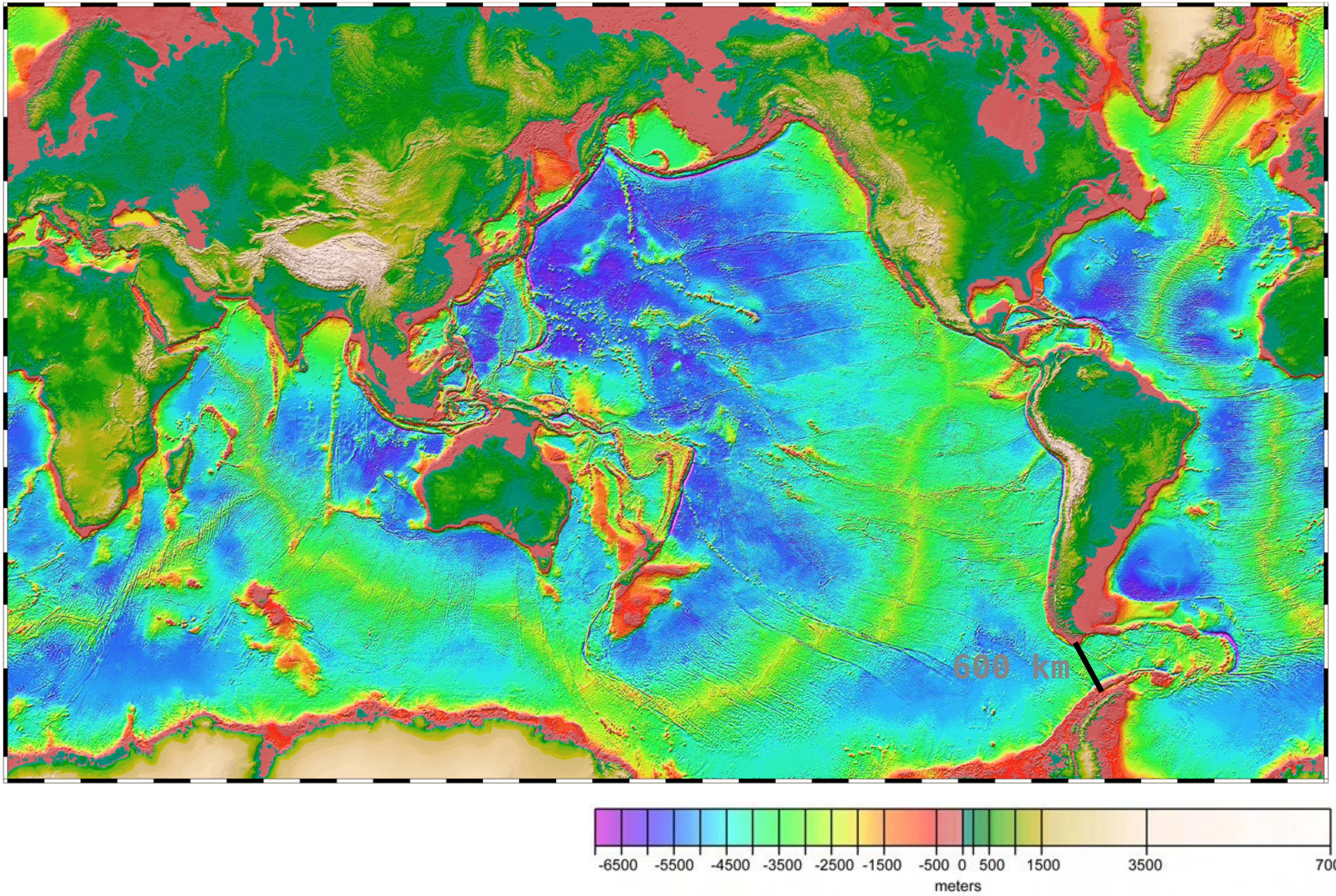
Polynyas :
Opening of the ocean
in the middle of sea ice



Difference #3: Boundaries

- The atmosphere has no boundaries.
  - The air can flow continuously without being blocked.
- All oceans are bounded by continents.
  - (Well, there is one exception: The Southern Ocean.)

Bathymetry


600 km
-6500
-5500
-4500
-3500
-2500
-1500
-500
0
500
1500
3500
7000
meters

Difference #4: Heating

- The atmosphere is heated from below.
    - Convection transport heat upward.
- The solar radiation heats the ocean surface.
    - Heating at the surface does not result in convection.
    - If the surface ocean becomes heavy, then convection can happen.

There are sources of geothermal heating at the bottom of the ocean but, in an average sense, this accounts for only a few milliwatts/m^2 of heat input, compared to air-sea heat fluxes of ±10 to 100W/m^2.

Difference #5: Stress

- The atmosphere does not get a stress from the ocean.
  - The air flows according to the state of the atmosphere.
- The ocean can be driven by winds.
  - Winds blowing over the ocean surface exert a stress.
  - The wind is a major driver of ocean circulation.

Physical characteristics of the ocean

1. The ocean basins

- The ocean covers 71% of the Earth's surface.
- Mean depth is 3.7 km
- The ocean's bottom topography is rougher than the land's surface.
- The ocean has huge heat capacity, approximately 1000 times that of the atmosphere.

2. The cryosphere

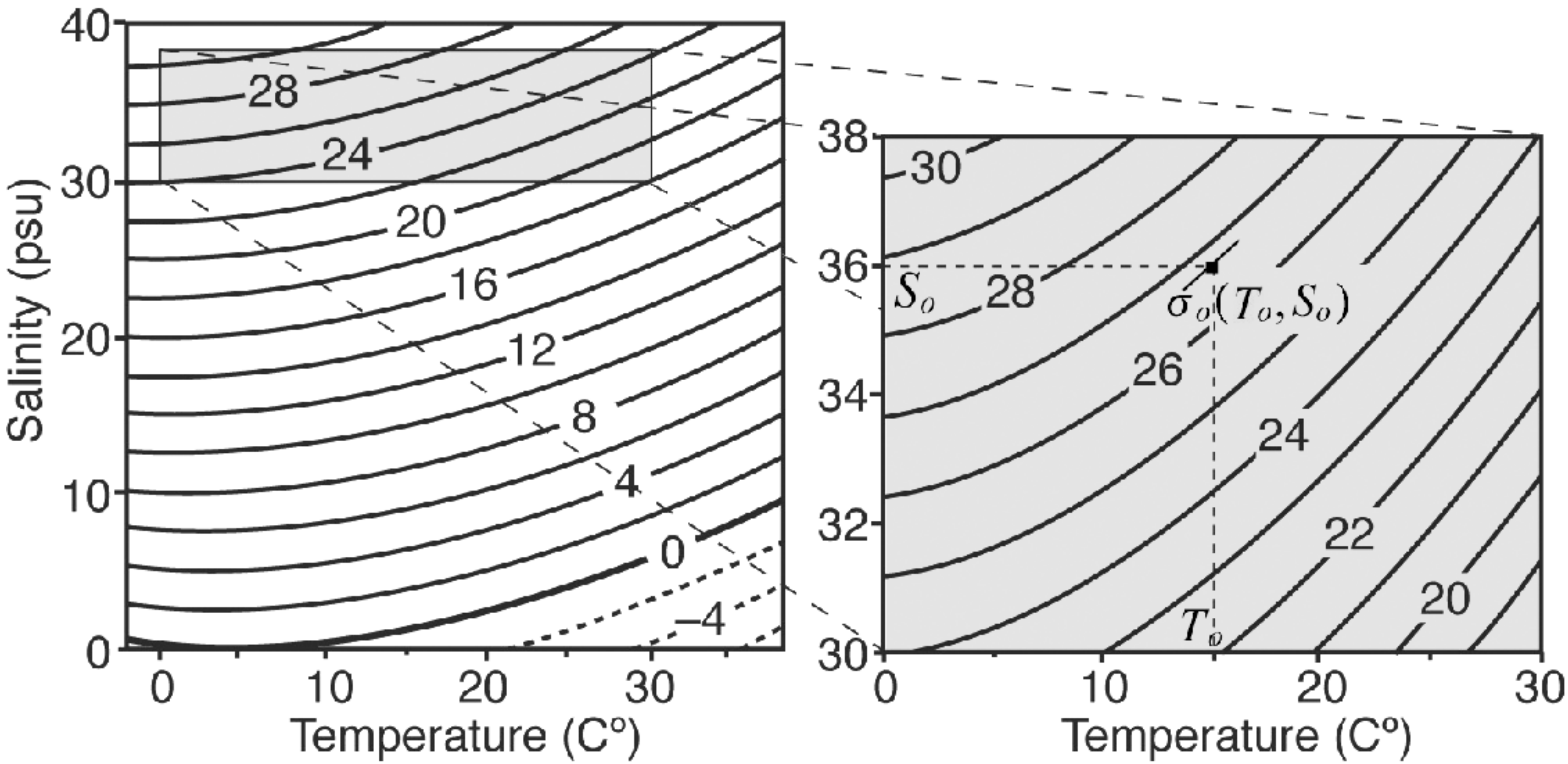
- Originated from Greek, it means “cold” “globe”.
- About 2% of the water is frozen in different forms like
  - Ice sheets, sea ice, snow, glaciers, frozen ground.
- Antarctica has 89% of frozen water. (The average depth of the ice sheet is 2 km.)
- It plays an important role in climate system with high albedo (70%).

3. Salinity

- A measure of amount of salt dissolved in the ocean
- The unit of salinity is about the ratio of salt in the water:
  - psu, g/kg, ‰
- The typical salinity is 34.5 psu = 34.5g of salt in 1kg of water.

4. The density

- The density of pure water at 4°C ≈ 1000 kg m^{-3}
- The mean density of the ocean ≈ 1035 kg m^{-3}, and varies very little.
- The density depends on temperature (T), salinity (S) and pressure (p) in a nonlinear manner : $\rho = \rho(T, S, p)$ → determined from lab measurements.
- The widely used property is density anomaly : $\sigma = \rho - \rho_{ref} = \rho - 1000$ kg m^{-3}



Contours of seawater density anomalies (σ)

4. The density

- Salty water is more dense than fresh water.
- Warm water is less dense than cold water.
- Fresh water has the maximum density at 4°C.
    - This is why ice forms on the top of freshwater lakes.
- Typically, temperature has greater impact on the density because it varies over the wide range (0 - 30°C)

Sensitivity of density to T and S

$$\alpha_T = -\frac{1}{\rho_{ref}}\frac{\partial \rho}{\partial T}$$

$$\beta_S = \frac{1}{\rho_{ref}}\frac{\partial \rho}{\partial S}$$

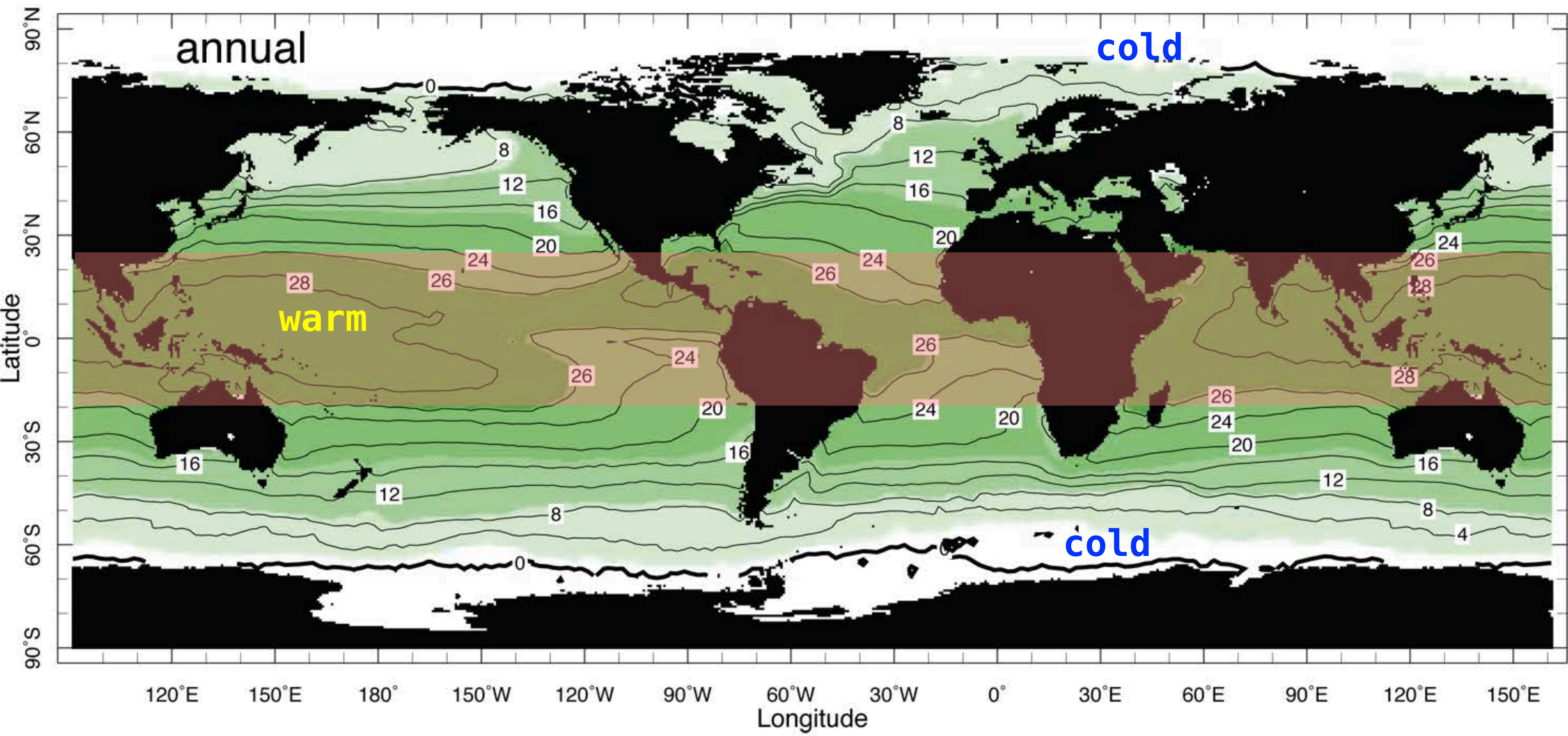
Surface			
T_o (°C)	–1.5	5	15
α_T ($\times 10^{-4}\,K^{-1}$)	0.3	1	2
S_o (psu)	34	36	38
β_S ($\times 10^{-4}\,psu^{-1}$)	7.8	7.8	7.6
σ_o ($kg\,m^{-3}$)	28	29	28
Depth of 1 km			
T_o (°C)	–1.5	3	13
α_T ($\times 10^{-4}\,K^{-1}$)	0.65	1.1	2.2
S_o (psu)	34	35	38
β_S ($\times 10^{-4}\,psu^{-1}$)	7.1	7.7	7.4
σ_o ($kg\,m^{-3}$)	–3	0.6	6.9

$$\sigma = \sigma_0 + \rho_{ref}\left(-\alpha_T\left[T - T_0\right] + \beta_S\left[S - S_0\right]\right)$$

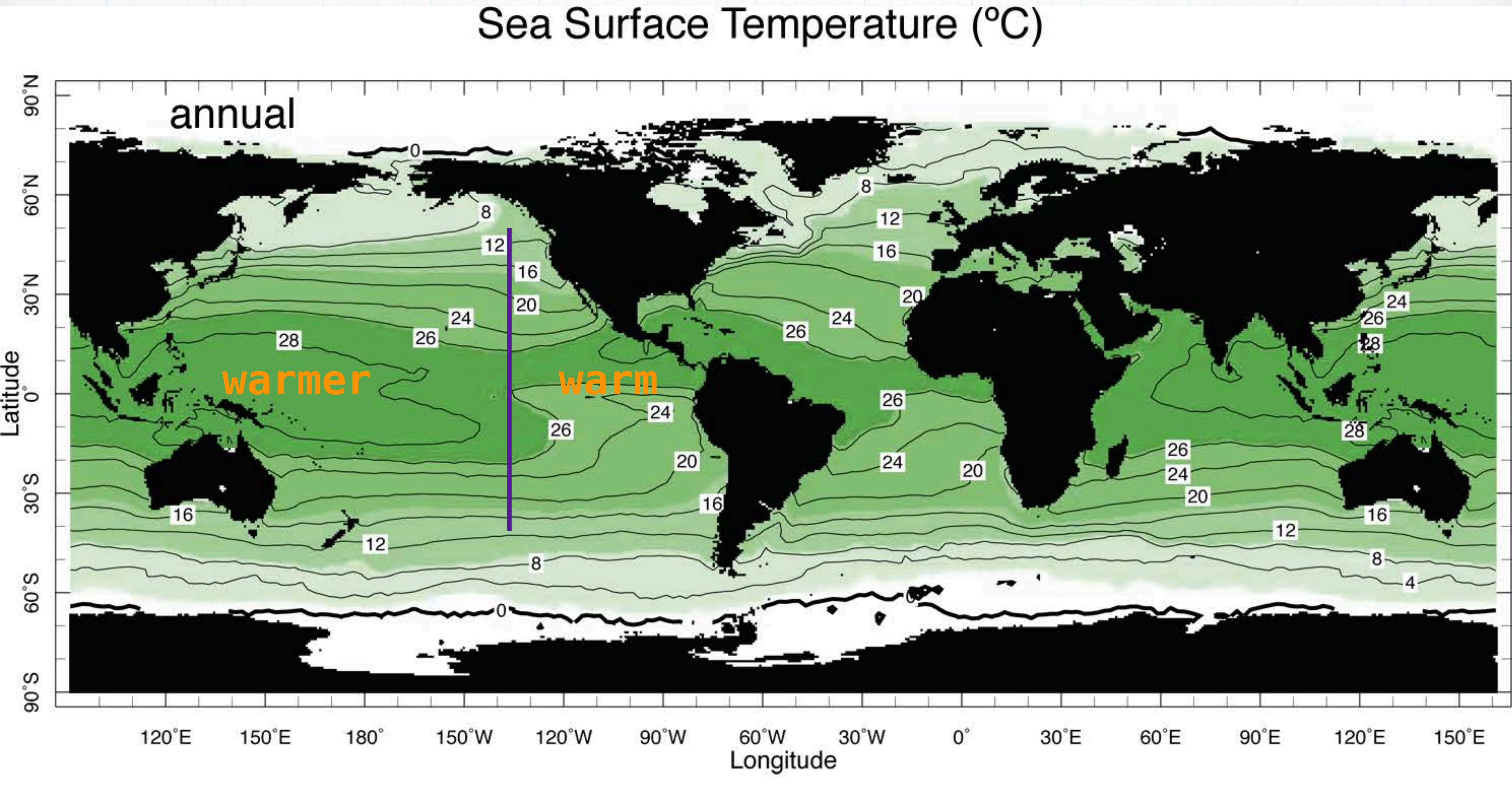
5. Temperature structure

Low albedo → heating at the surface

Sea Surface Temperature (ºC)



5. Temperature structure



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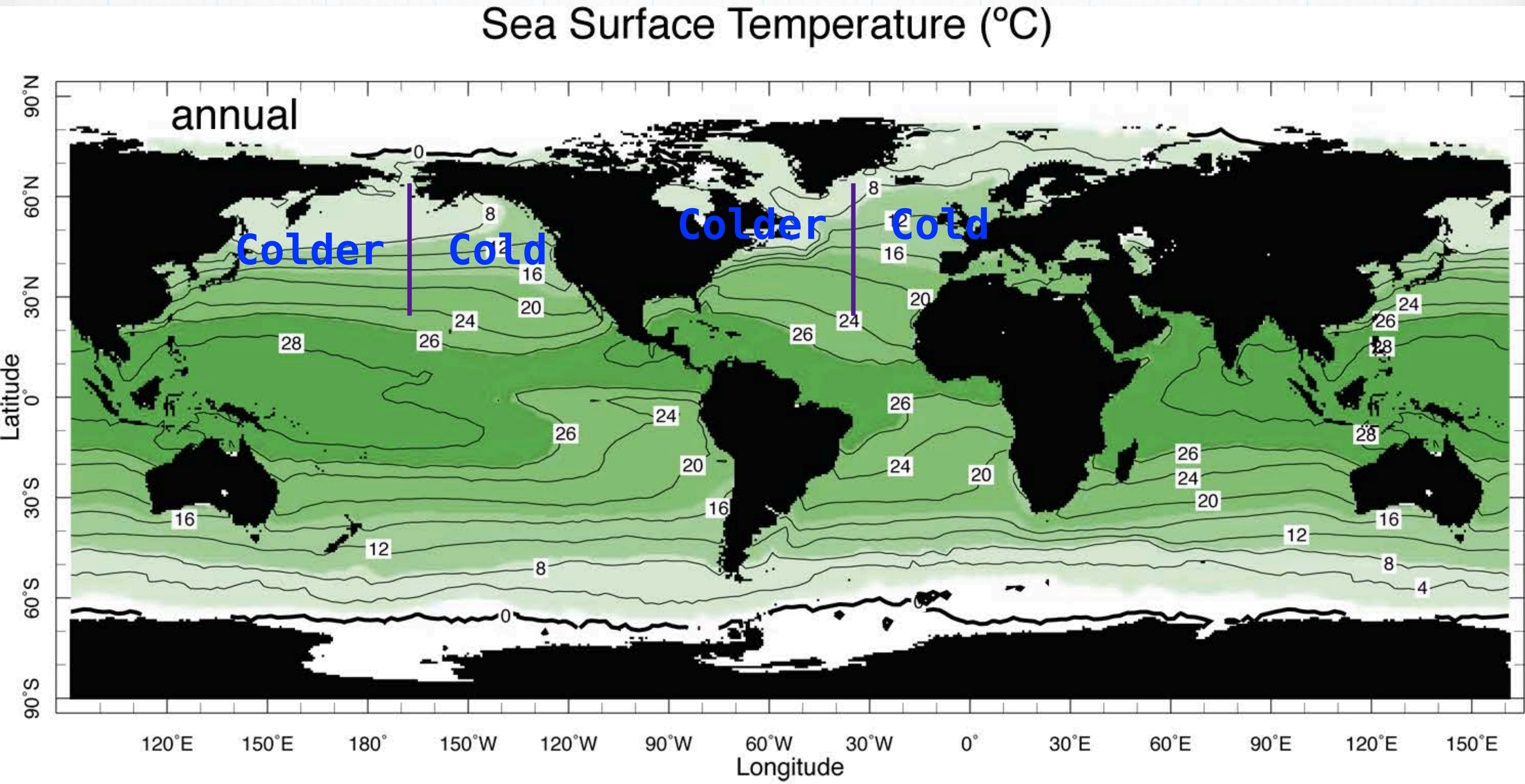

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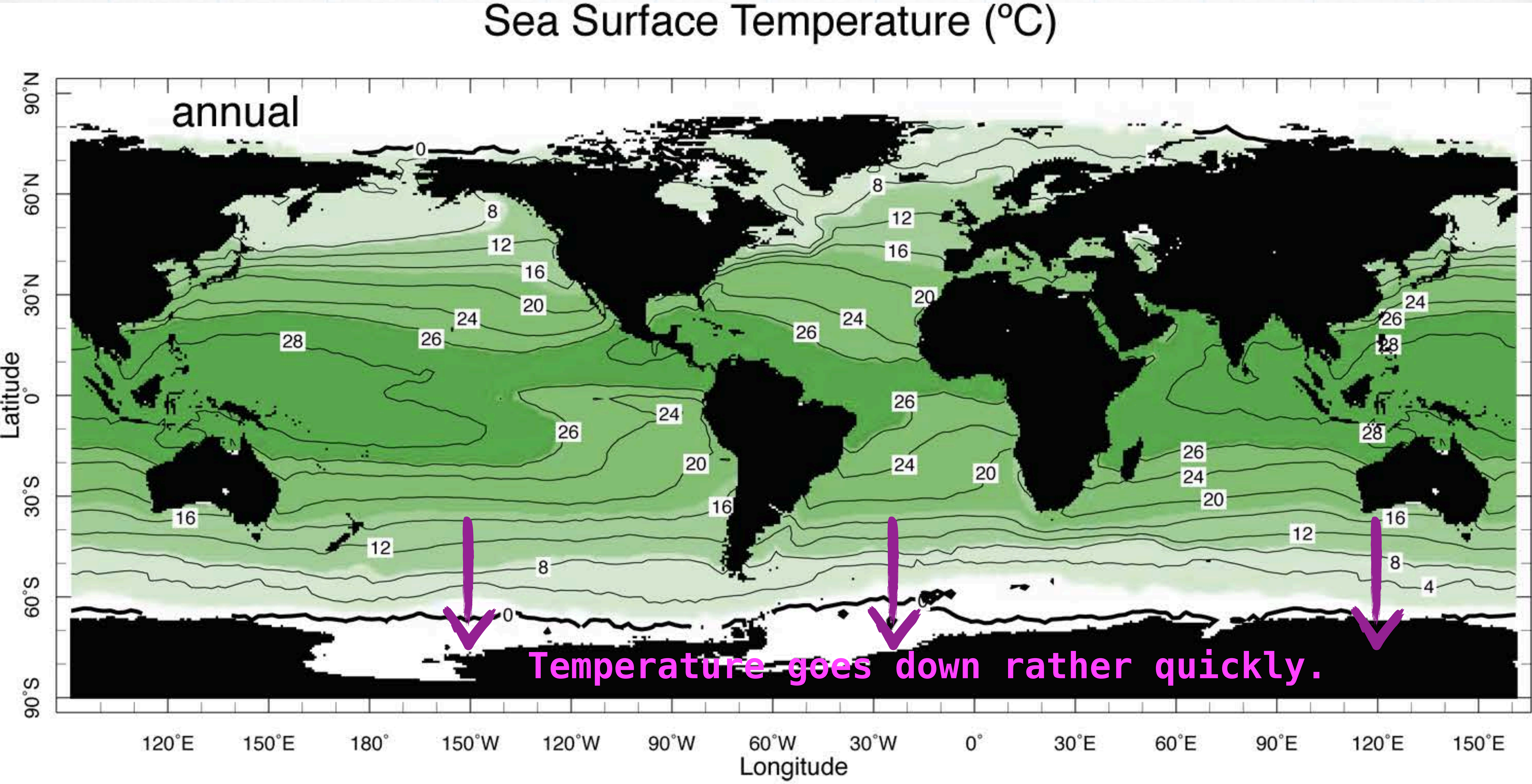
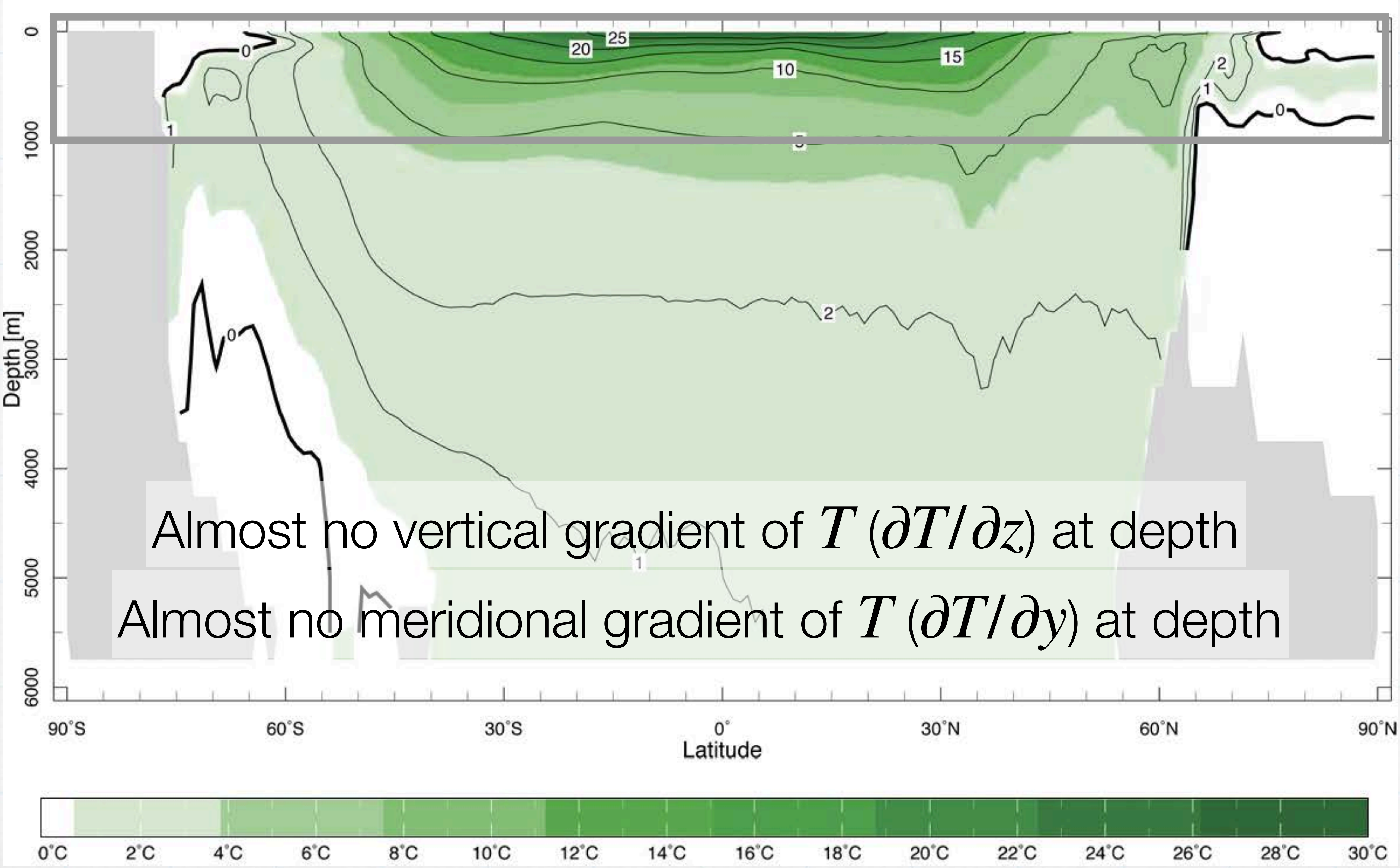


5. Temperature structure: zonal-average mean



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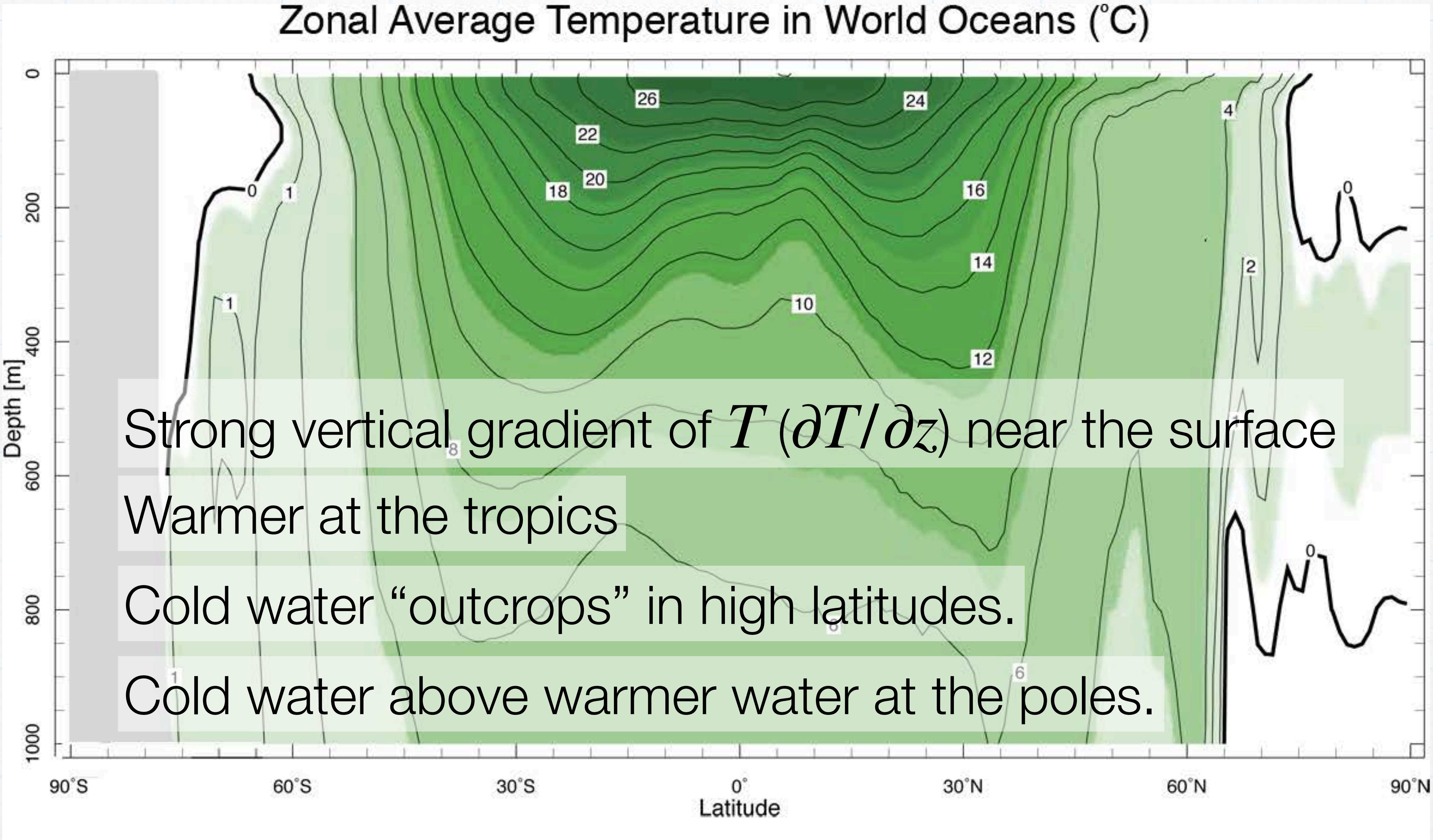


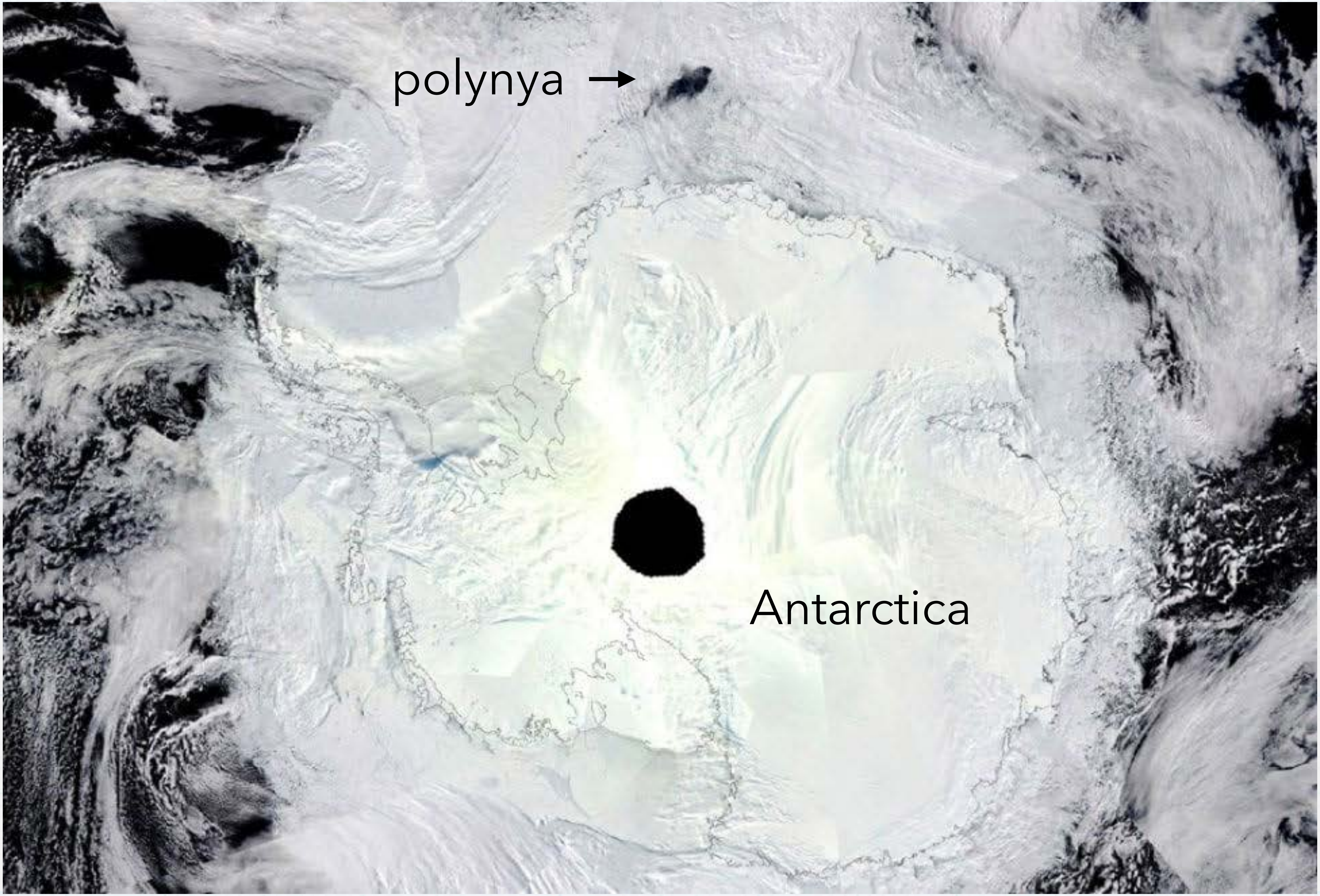
Strong vertical gradient of T ($\partial T/\partial z$) near the surface

Warmer at the tropics

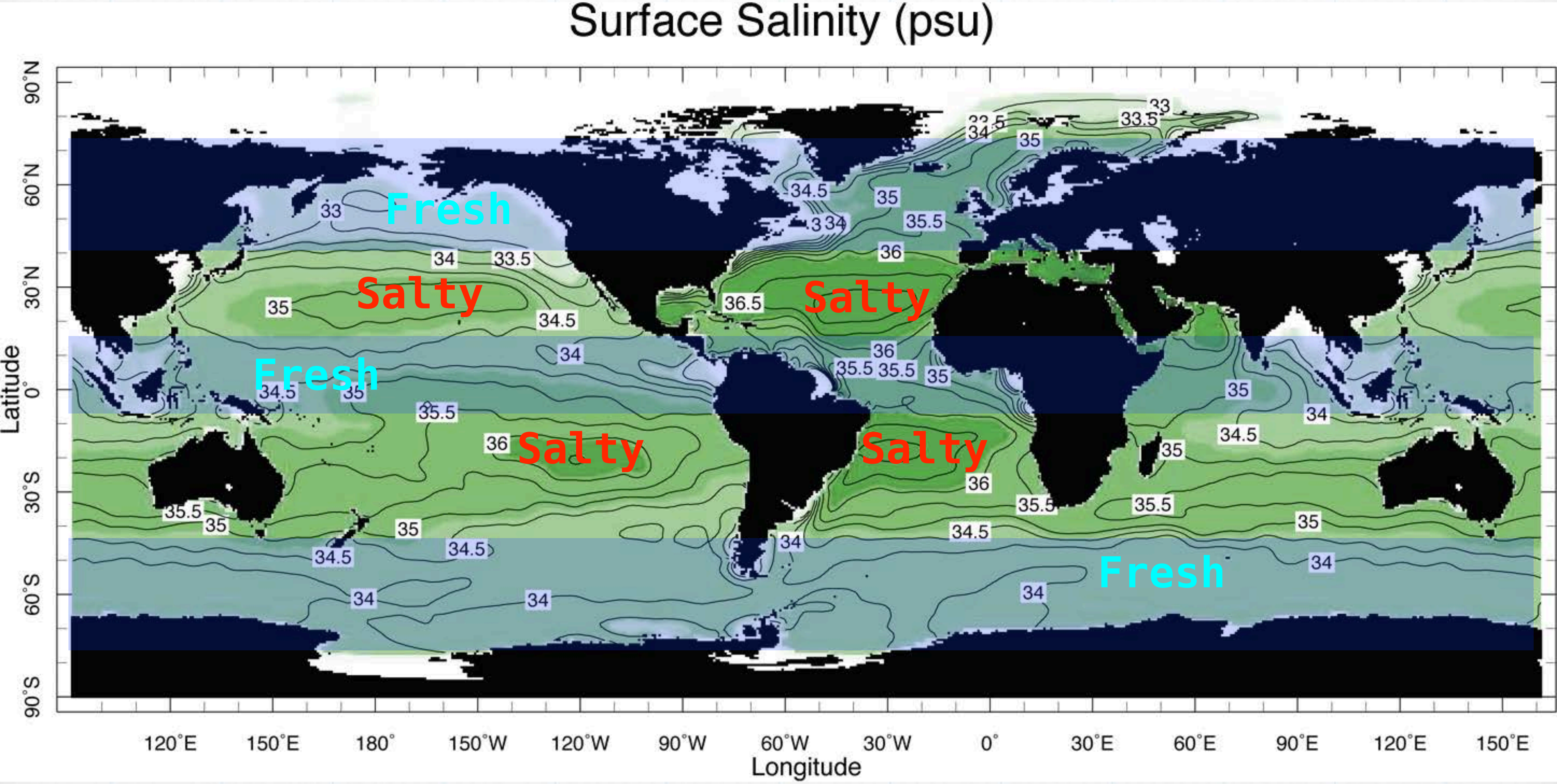
Cold water "outcrops" in high latitudes.

Cold water above warmer water at the poles.

2017



5. Salinity structure



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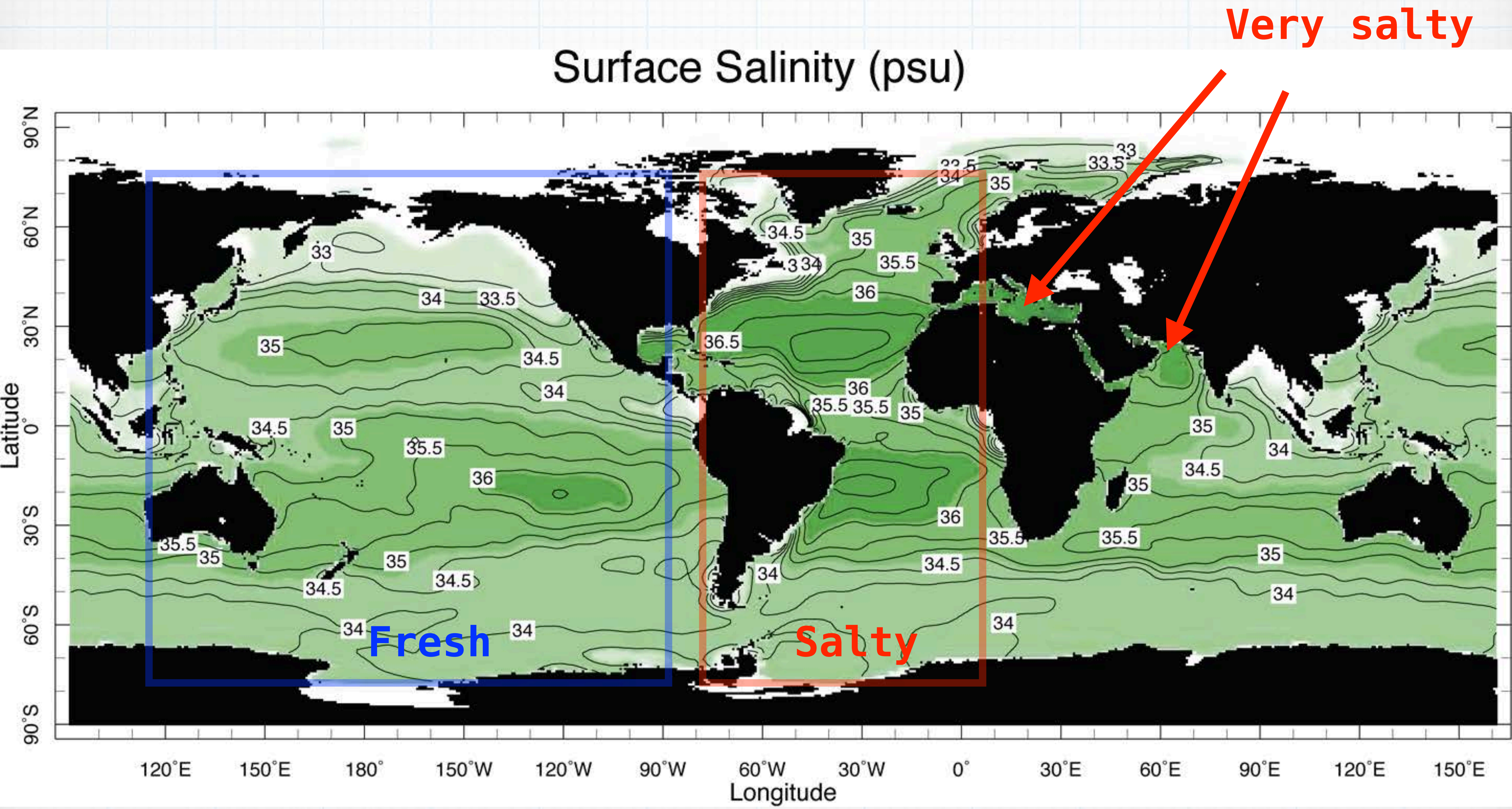

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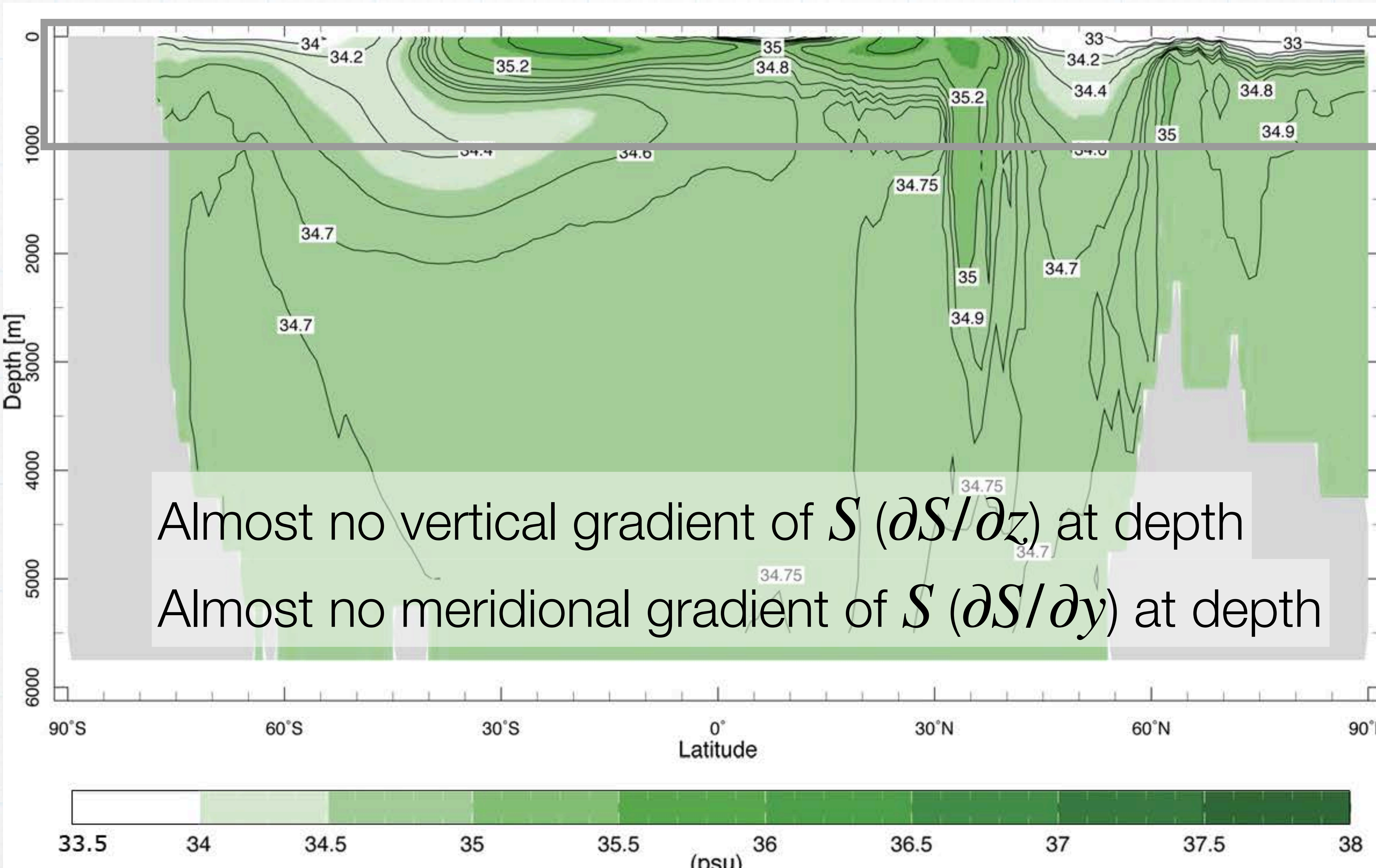
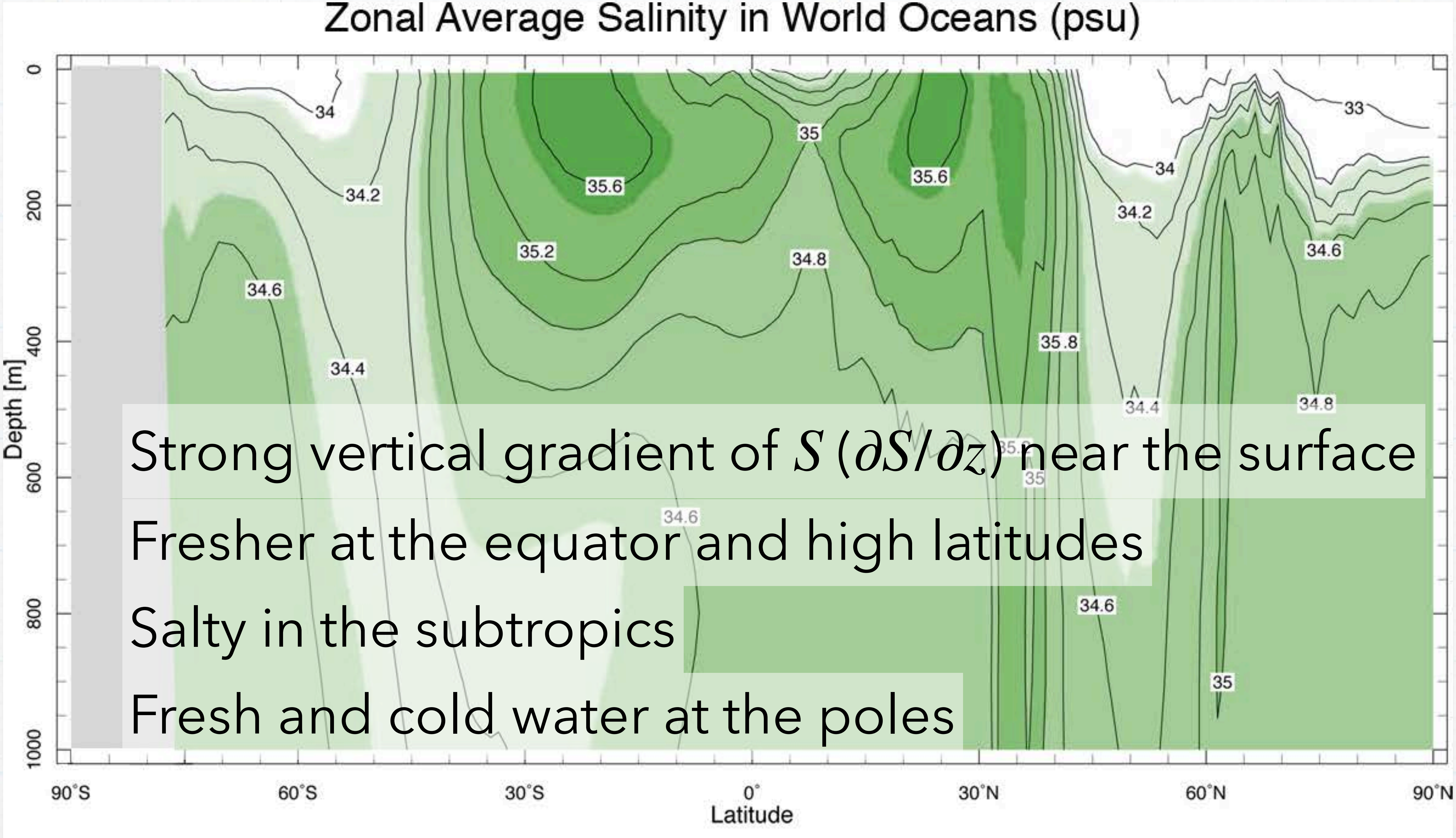


Almost no vertical gradient of S ($\partial S/\partial z$) at depth

Almost no meridional gradient of S ($\partial S/\partial y$) at depth

5. Salinity structure : zonal-average mean



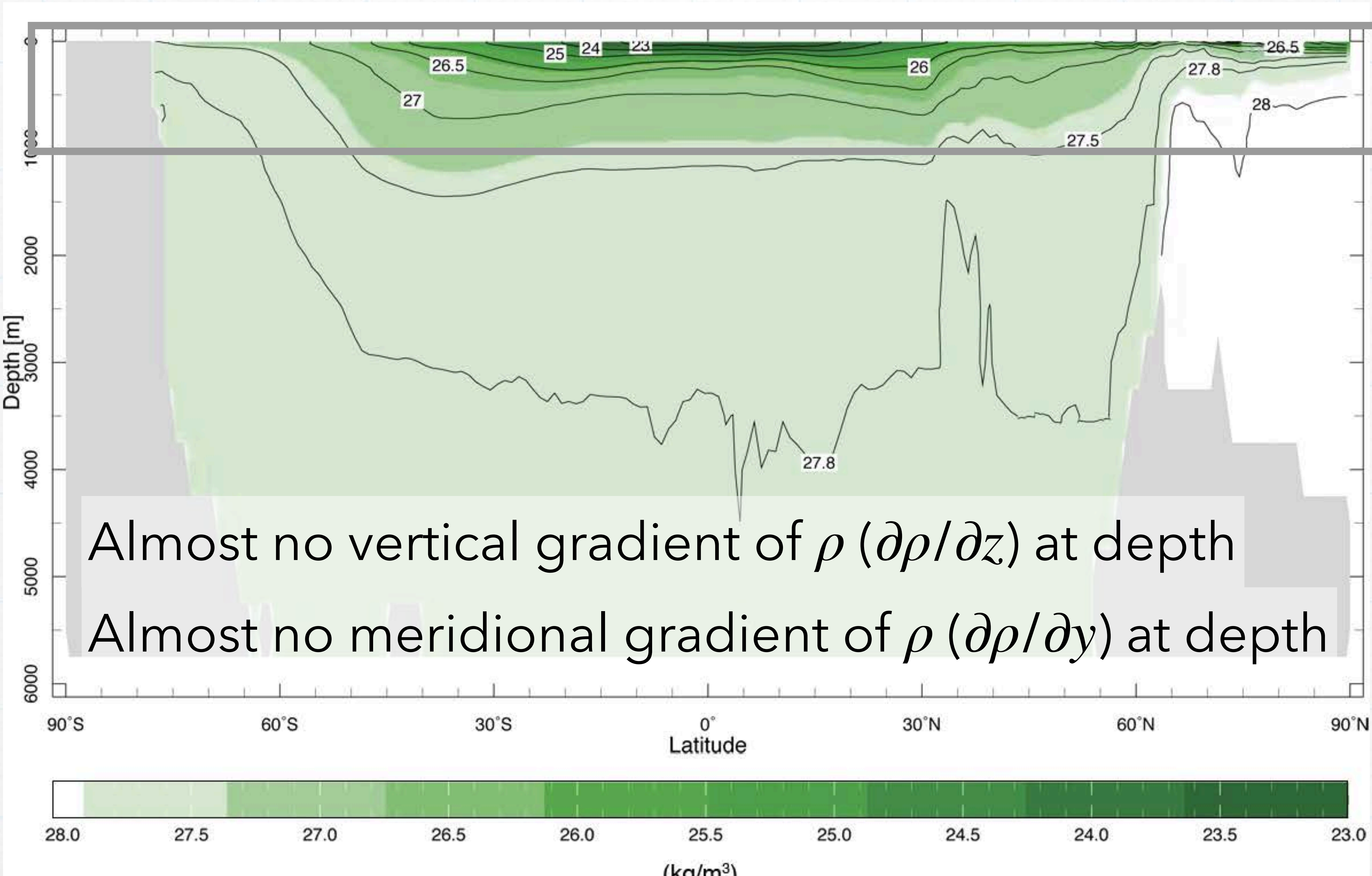
Strong vertical gradient of S ($\partial S/\partial z$) near the surface

Fresher at the equator and high latitudes

Salty in the subtropics

Fresh and cold water at the poles

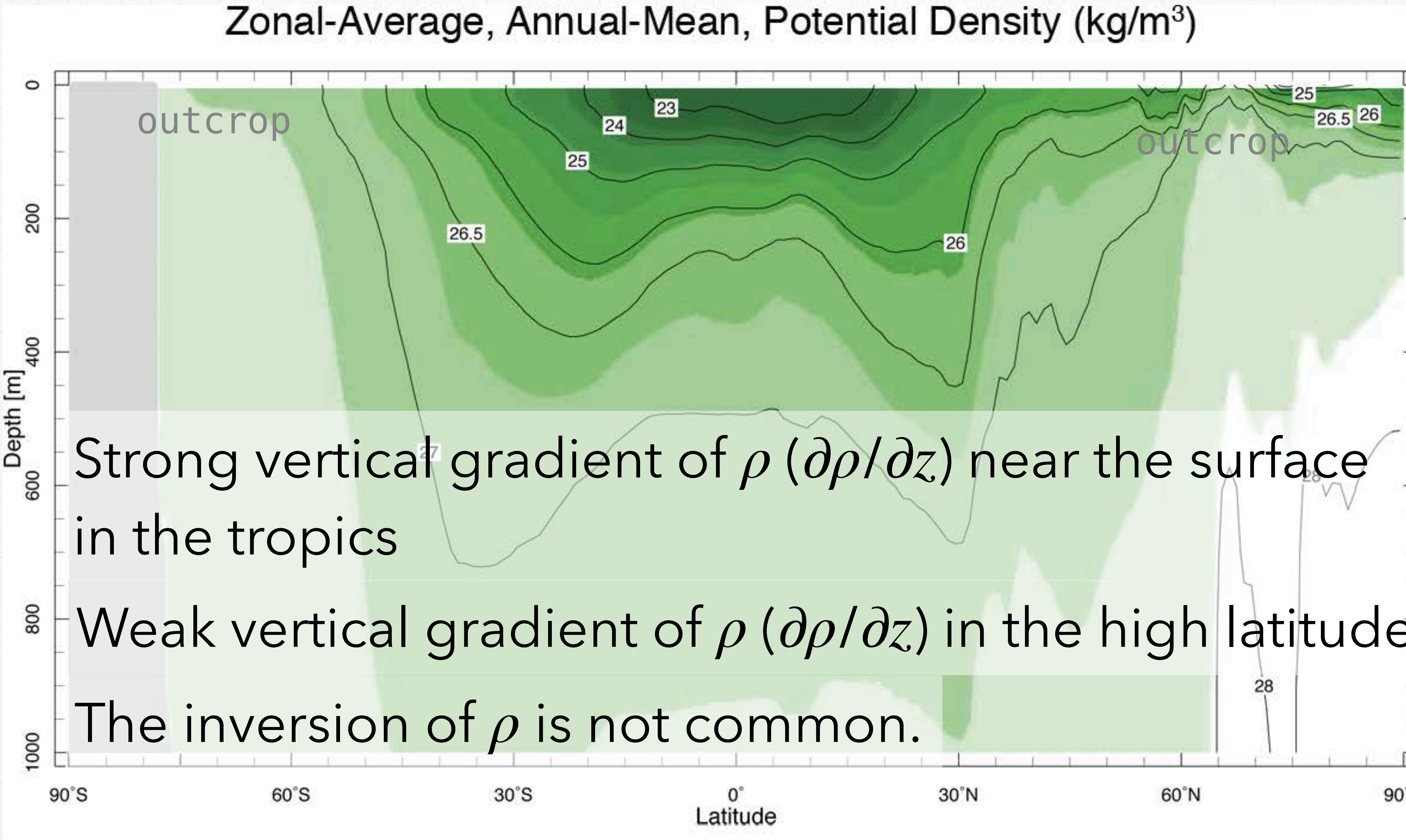
6. Density structure : zonal-average mean



Almost no vertical gradient of ρ ($\partial\rho/\partial z$) at depth

Almost no meridional gradient of ρ ($\partial\rho/\partial y$) at depth

6. Density structure : zonal-average mean

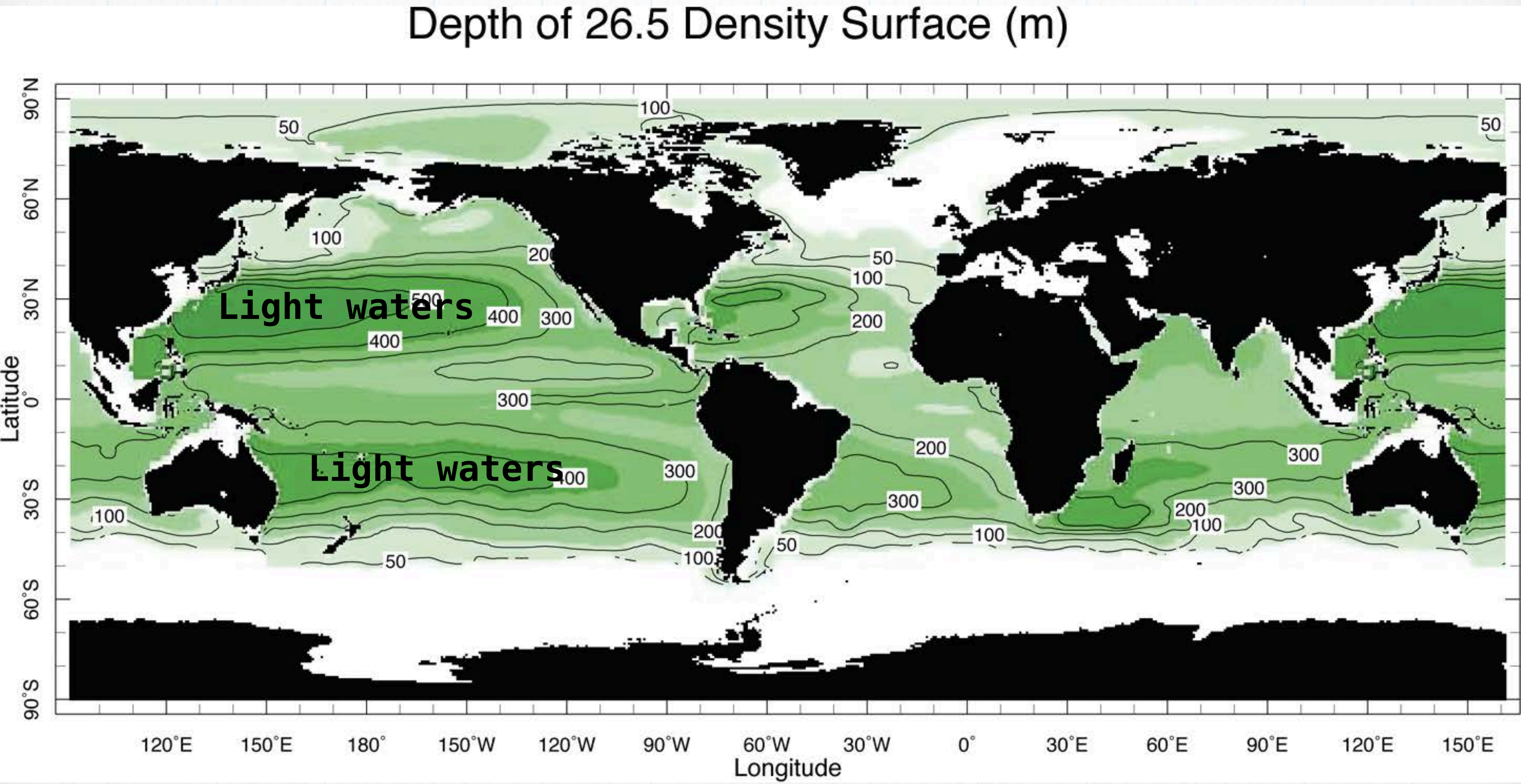


Strong vertical gradient of ρ $(\partial\rho/\partial z)$ near the surface in the tropics

Weak vertical gradient of ρ $(\partial\rho/\partial z)$ in the high latitudes

The inversion of ρ is not common.

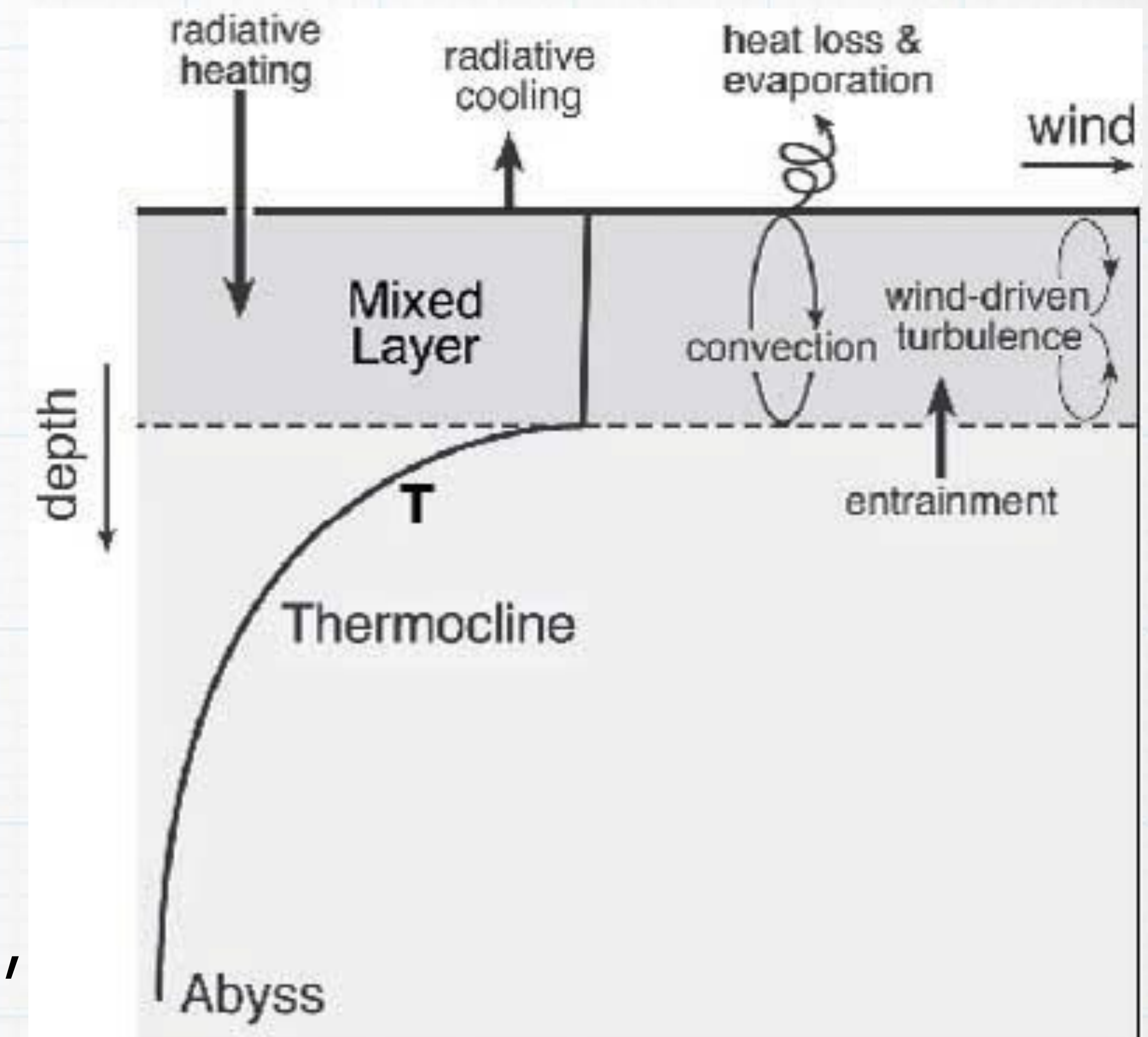
6. The depth of 26.5 density surface



The mixed layer

- At the surface of the ocean, there is a well-defined mixed layer.
- Stirred by wind and convection
- Properties are relatively uniform in the vertical.
- Communicates with thermocline (in high latitudes, with abyss)

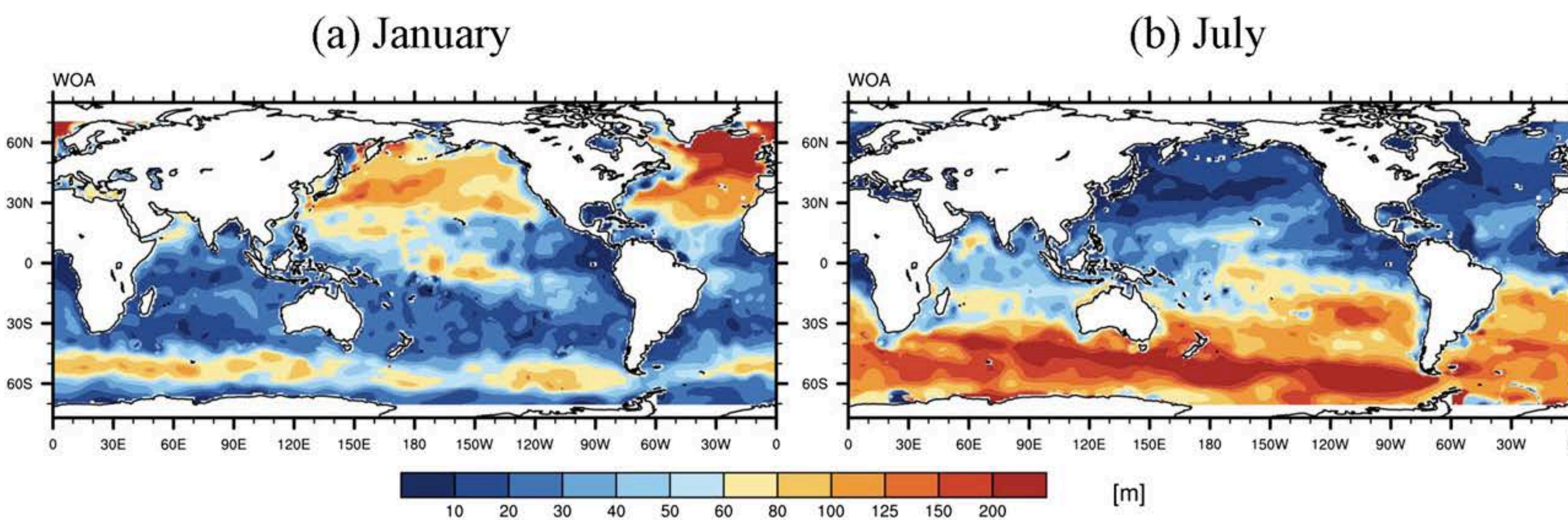
Heat gain Heat loss



IR is absorbed within a few mm, blue/green light may penetrate to almost 100m in especially clear water, but is usually attenuated much more rapidly.

The mixed layer

- The typical depth of the mixed layer is 50-100 m.
- At high latitudes, mixed layer depth can be a few hundred meters, even up to 1 km.



Noh et al., 2016

Buoyancy

- An upward force

$$b = -g\frac{\rho_p - \rho_e}{\rho_p} \approx -\frac{g}{\rho_e}\frac{\partial \rho_e}{\partial z}\Delta = N^2\Delta$$

- Buoyancy frequency :

$$N^2 = -\frac{g}{\rho_{ref}}\frac{\partial \rho_e}{\partial z} \approx g\alpha_T\frac{\partial T}{\partial z}$$

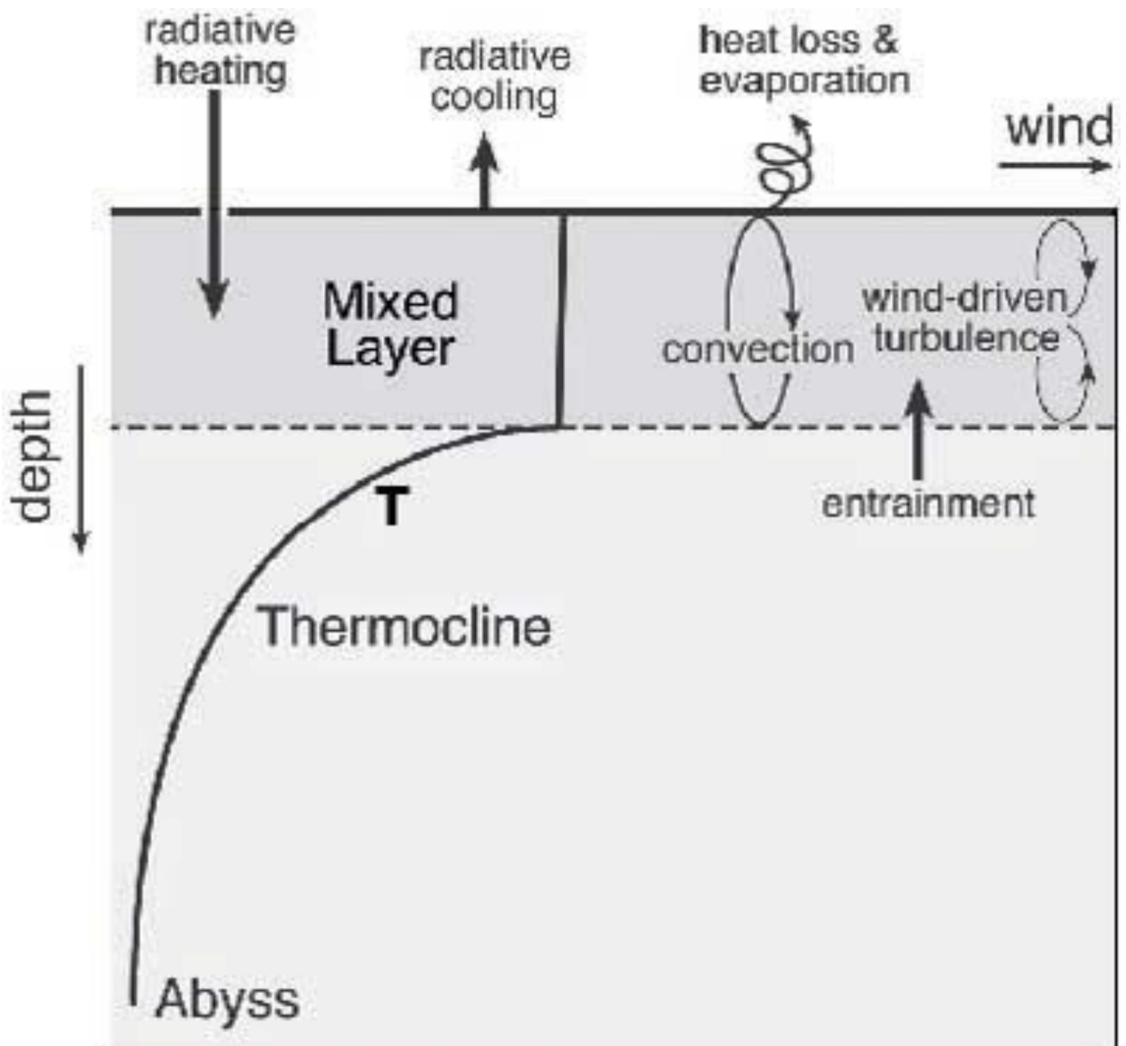
$$N^2 = -\frac{g}{\rho_{ref}}\frac{\partial \rho_e}{\partial z} \approx g\alpha_T\frac{\partial T}{\partial z} = 10 \times 2 \times 10^{-4} \times \frac{15}{1000} = 30 \times 10^{-6}\ \mathrm{s}^{-2}$$

α_T: 2x10^{-4} K^{-1}

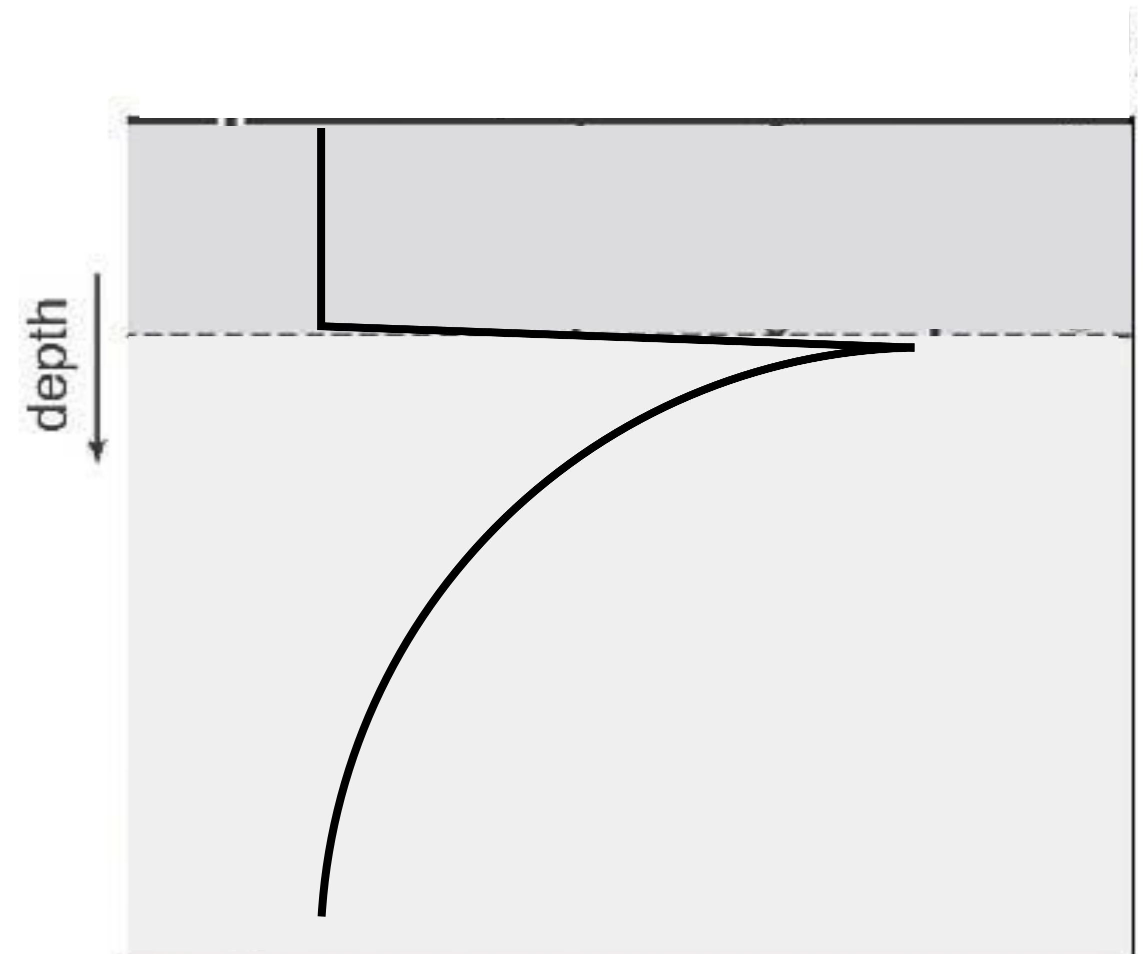
Period = 2π / N
= 20 mins

Roughly twice that of
atmospheric gravity waves

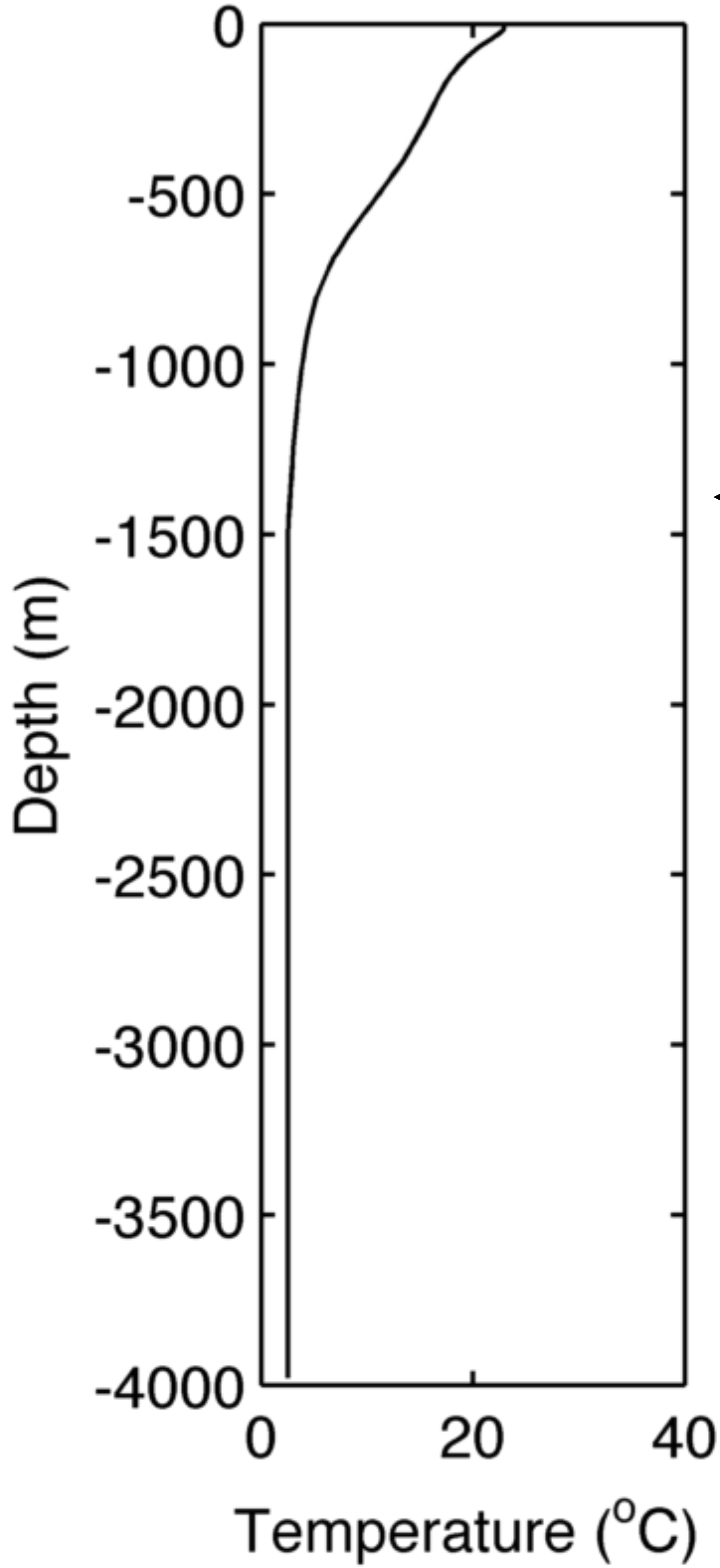
Temperature



Buoyancy frequency

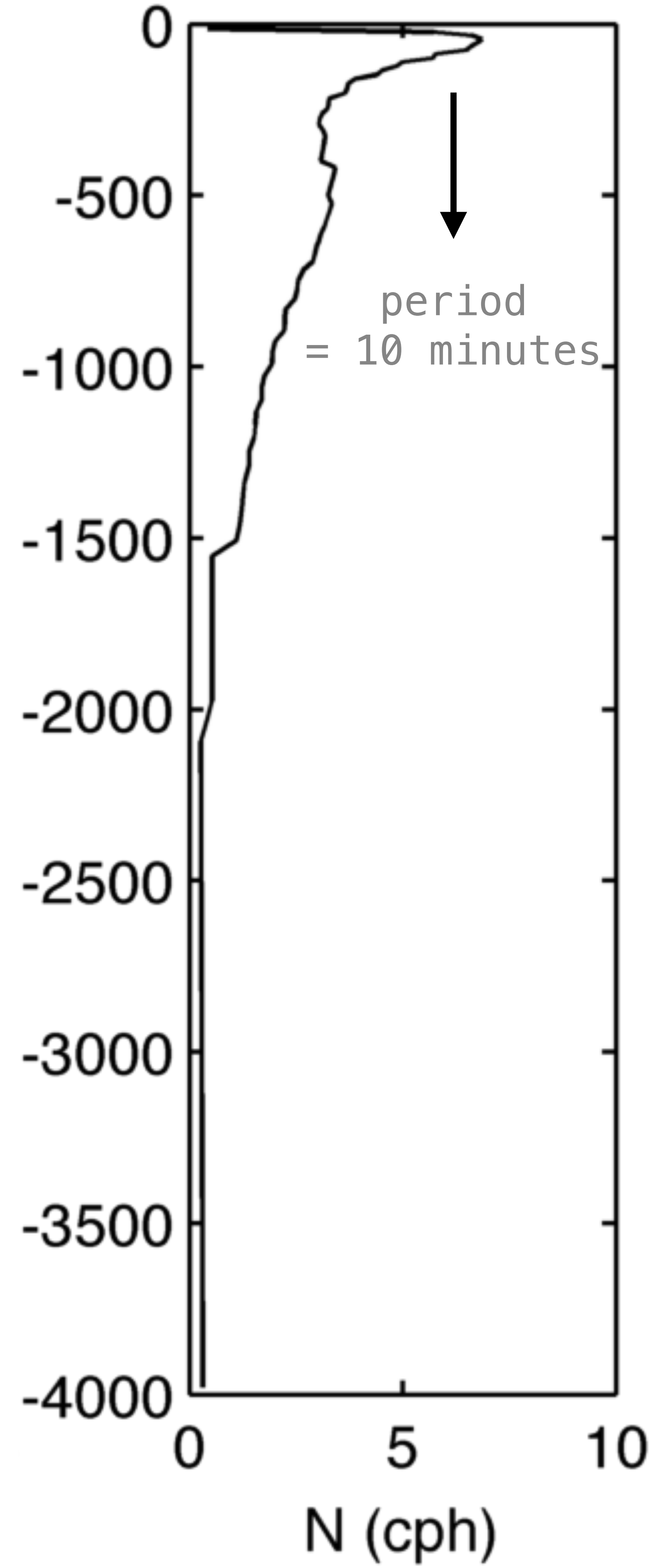


Observation



Temperature

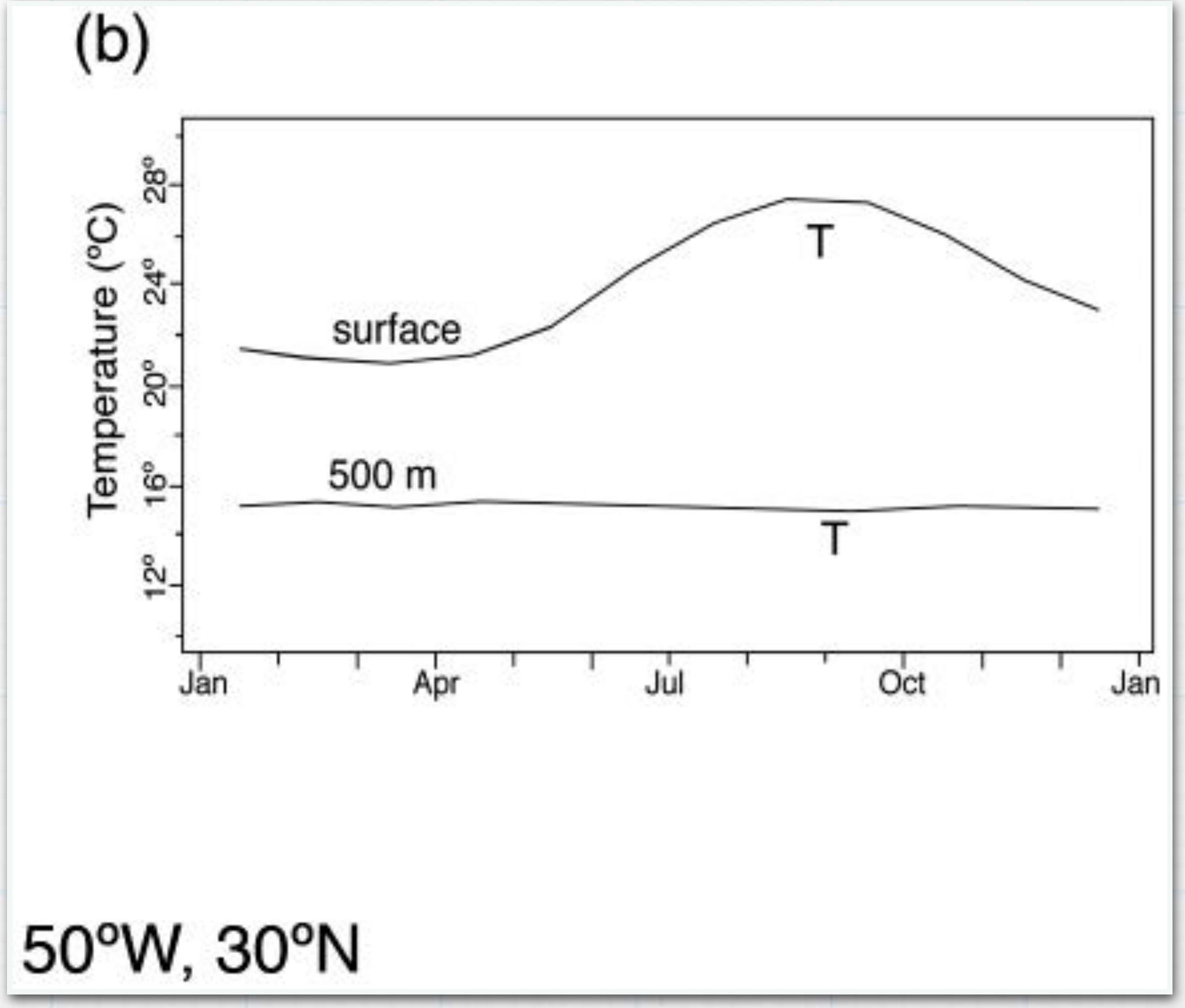
N



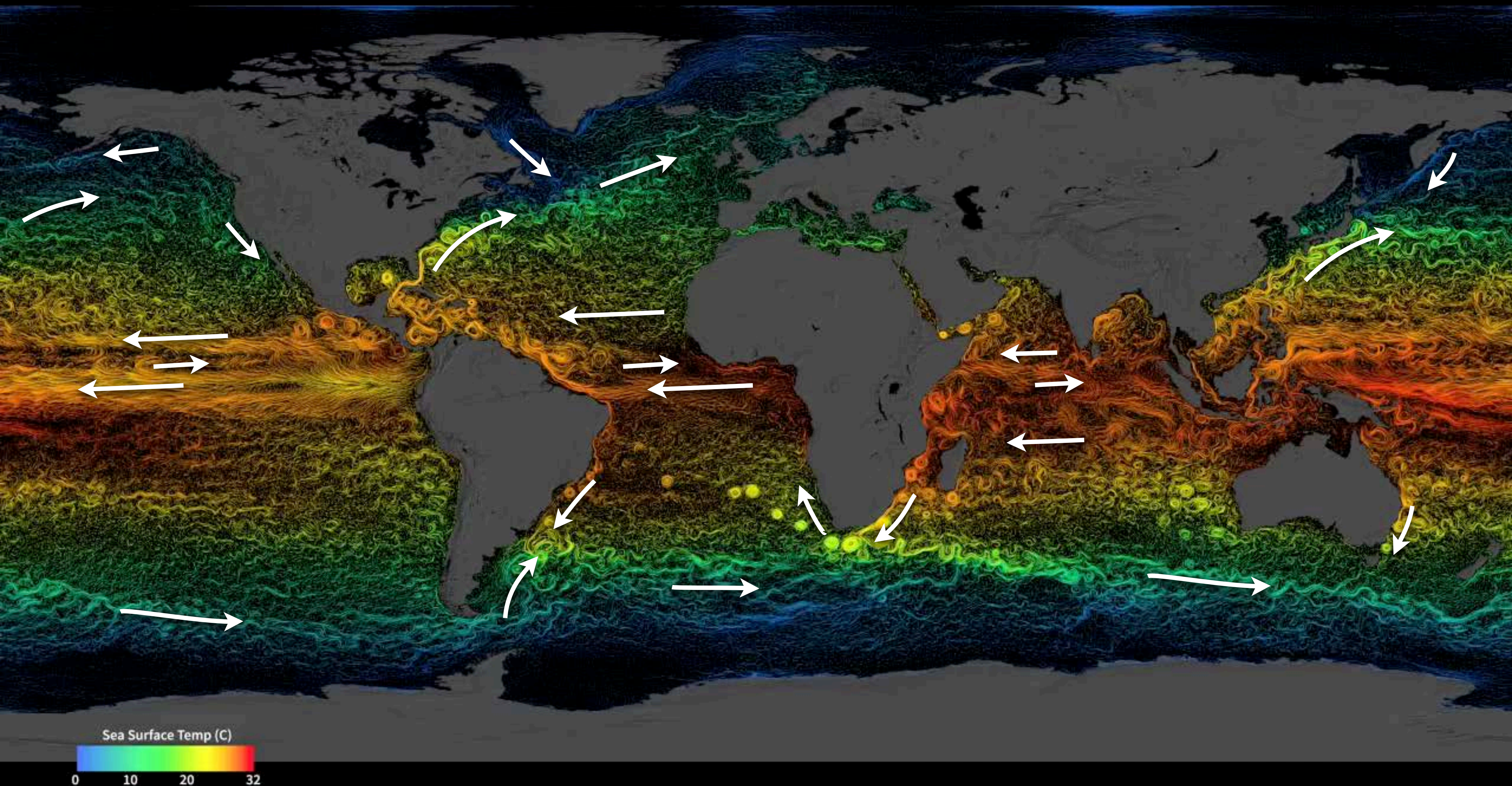
What part of the ocean can be mixed well?

Vertical mixing

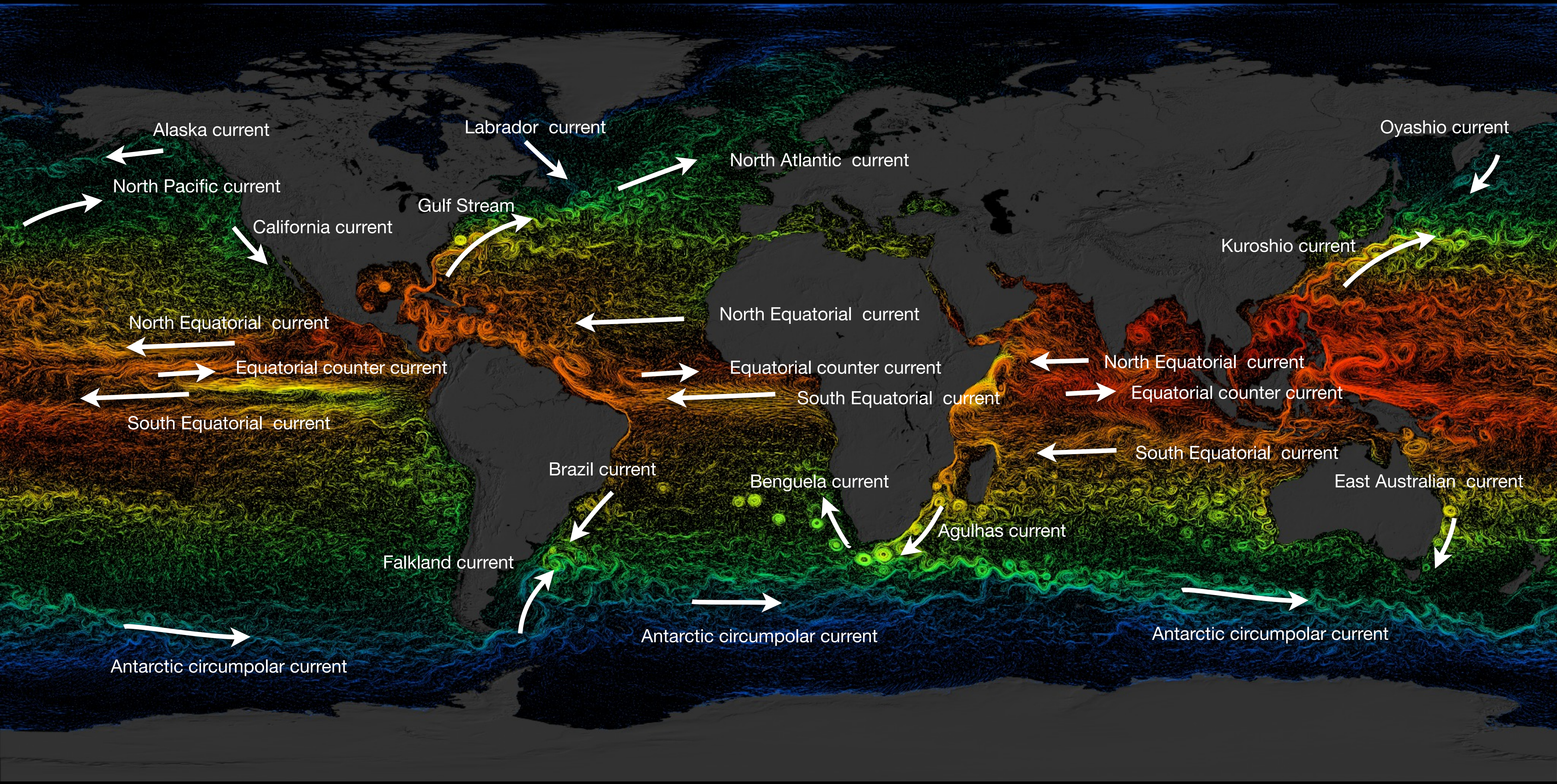
- The internal gravity waves can contribute to mixing when breaking
  - The effect of mixing in the thermocline is rather weak.
  - The effect of mixing in the abyss is much larger.
- The mixed layer responds quickly to the atmospheric forcing.
- Interior ocean does not show much variability.

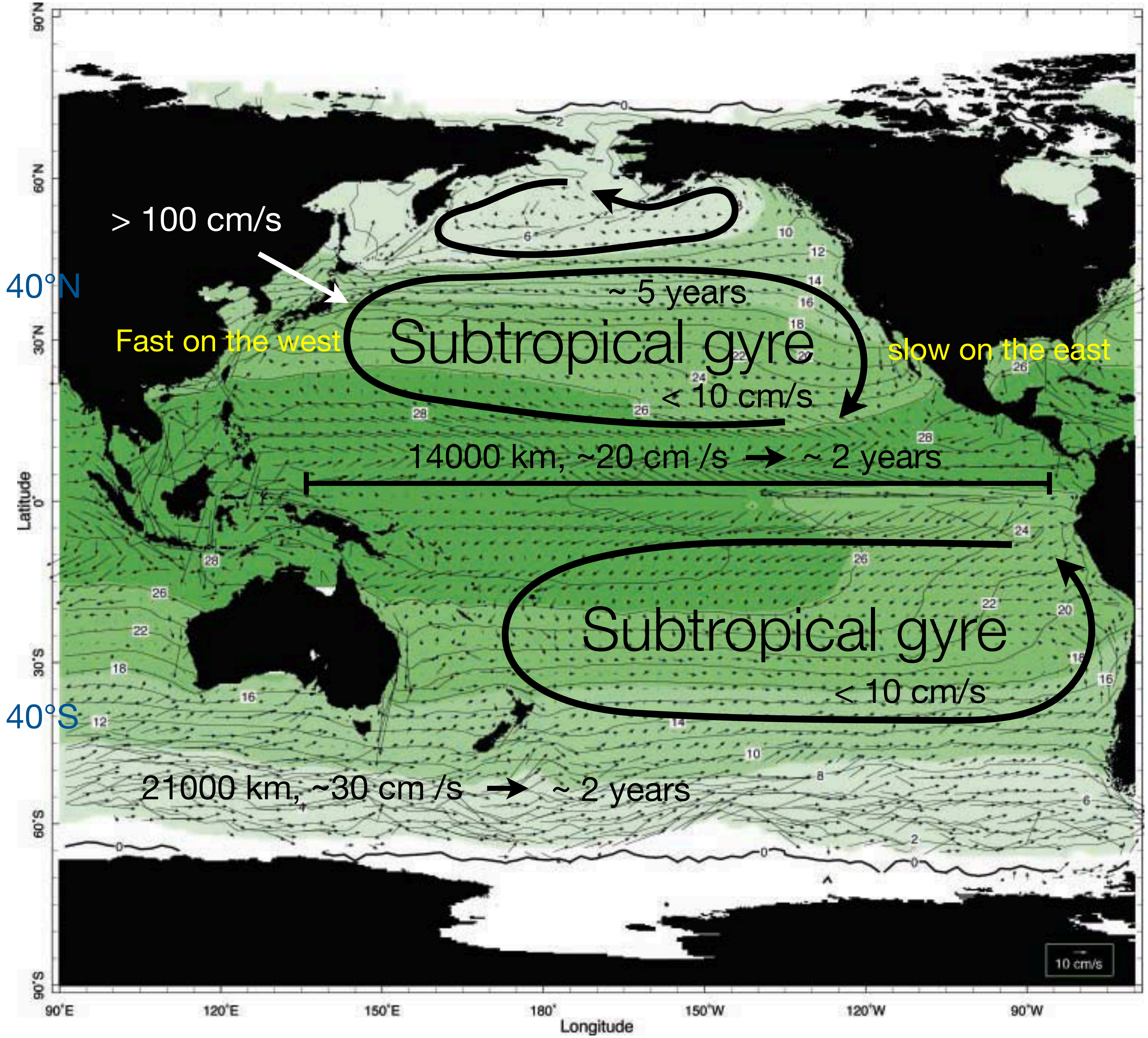


Global Sea Surface Currents and Temperature

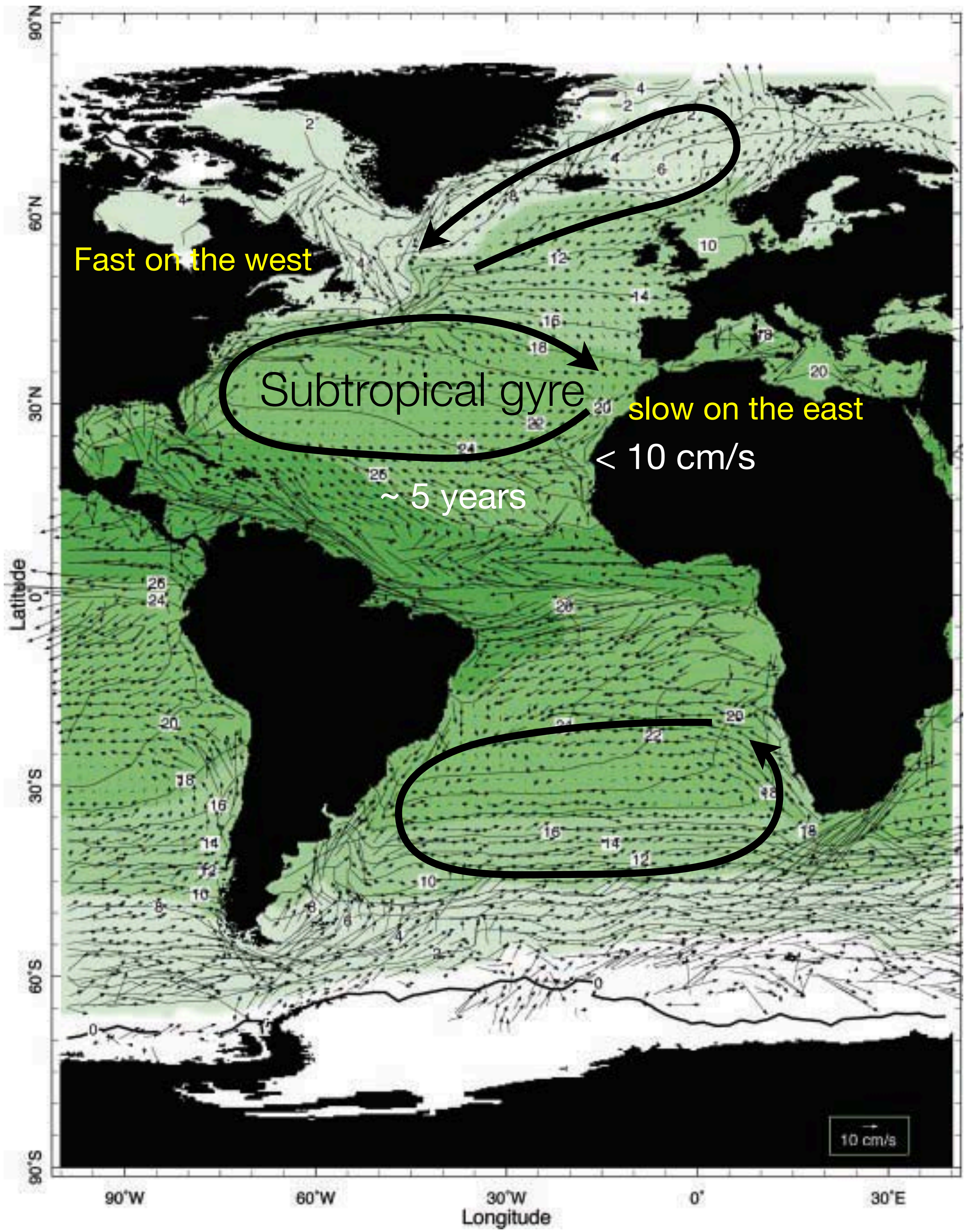


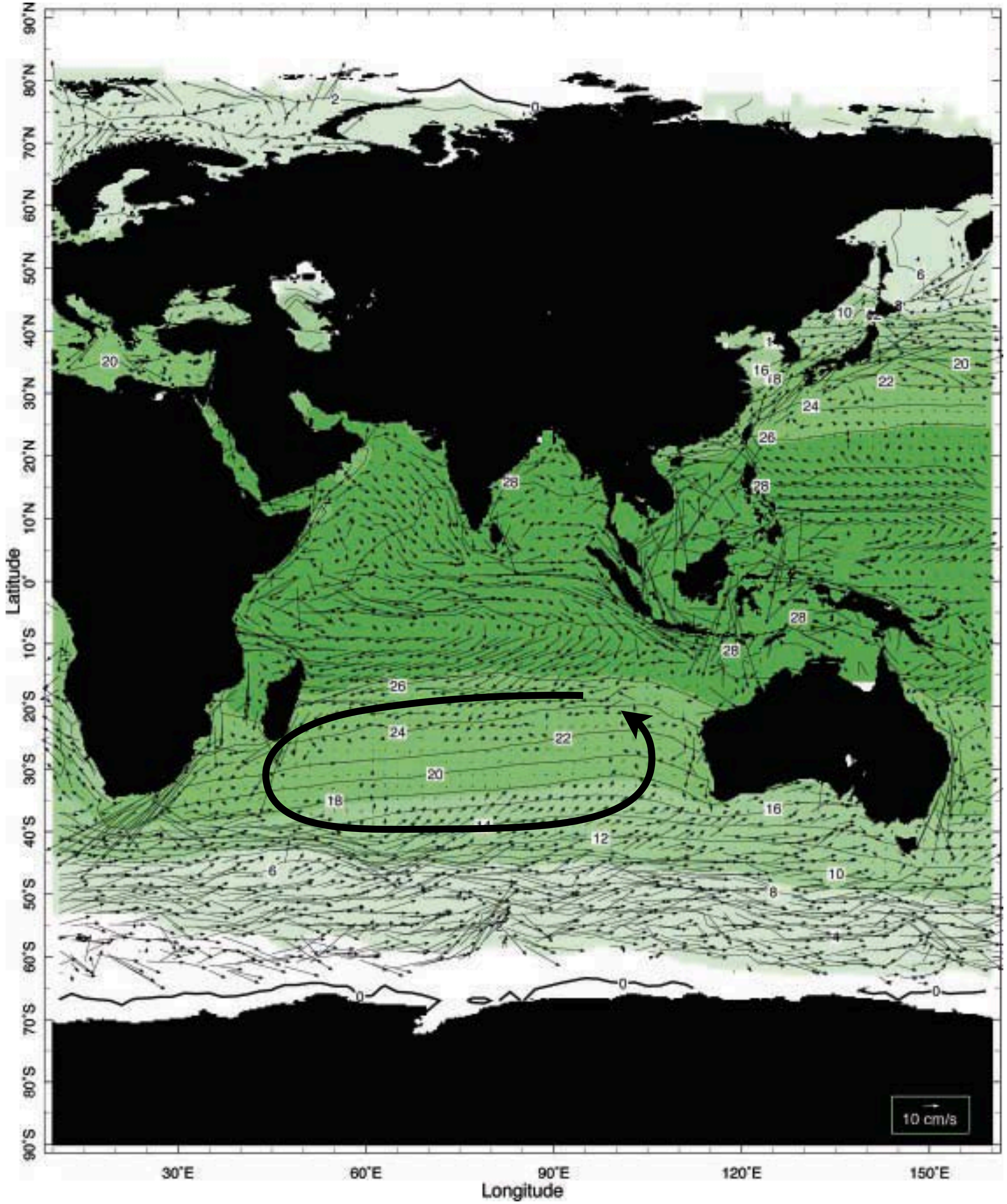
https://svs.gsfc.nasa.gov/3912


Alaska current
Labrador current
Oyashio current
North Atlantic current
North Pacific current
Gulf Stream
California current
Kuroshio current
North Equatorial current
North Equatorial current
Equatorial counter current
Equatorial counter current
North Equatorial current
South Equatorial current
Equatorial counter current
South Equatorial current
South Equatorial current
Brazil current
Benguela current
East Australian current
Agulhas current
Falkland current
Antarctic circumpolar current
Antarctic circumpolar current
Antarctic circumpolar current



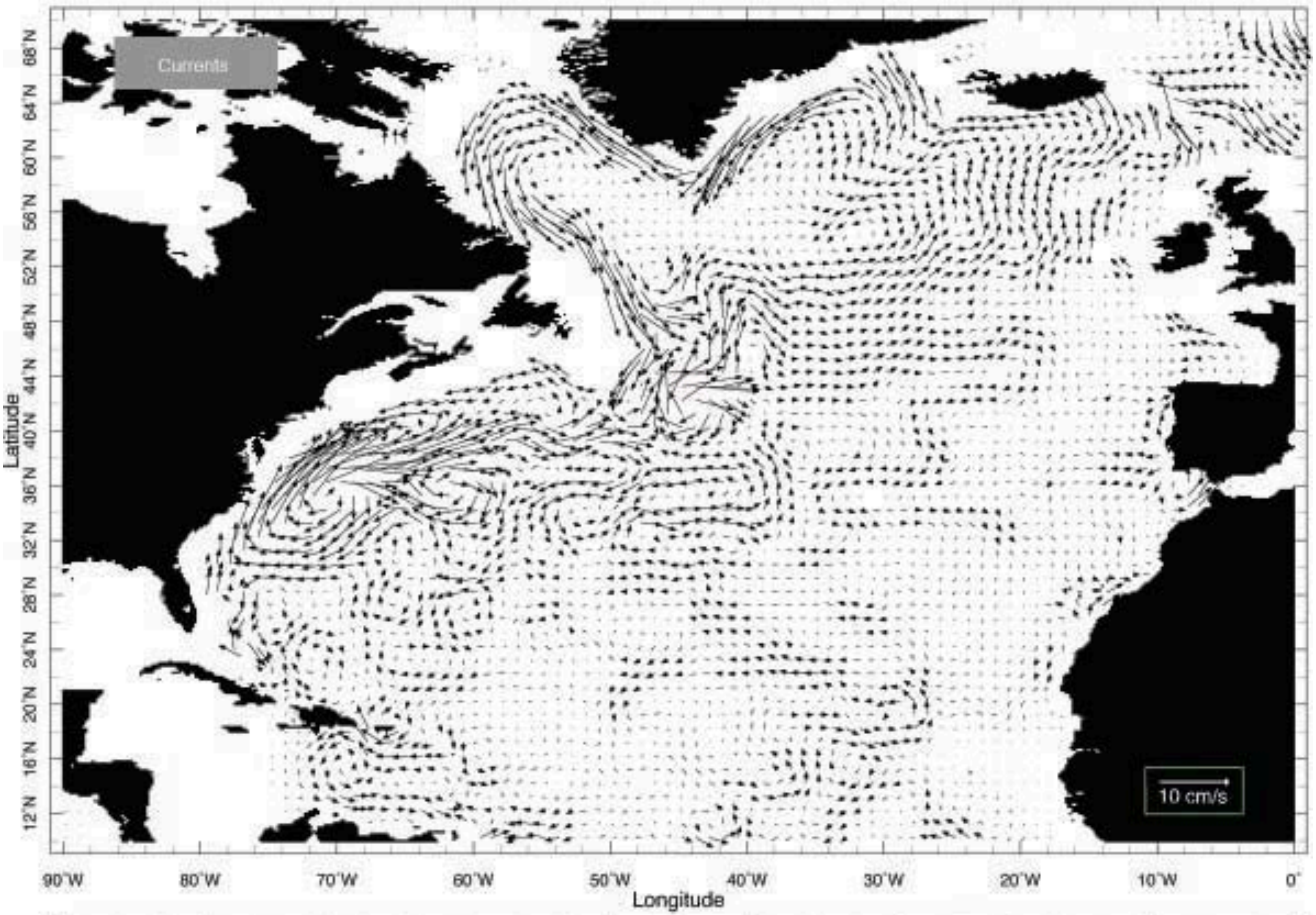
40°N
40°S
> 100 cm/s
Fast on the west
slow on the east
~ 5 years
Subtropical gyre
< 10 cm/s
14000 km, ~20 cm /s → ~ 2 years
Subtropical gyre
< 10 cm/s
21000 km, ~30 cm /s → ~ 2 years
10 cm/s
Latitude
Longitude
90°E
120°E
150°E
180°
150°W
120°W
90°W
90°N
60°N
30°N
0°
30°S
60°S
90°S

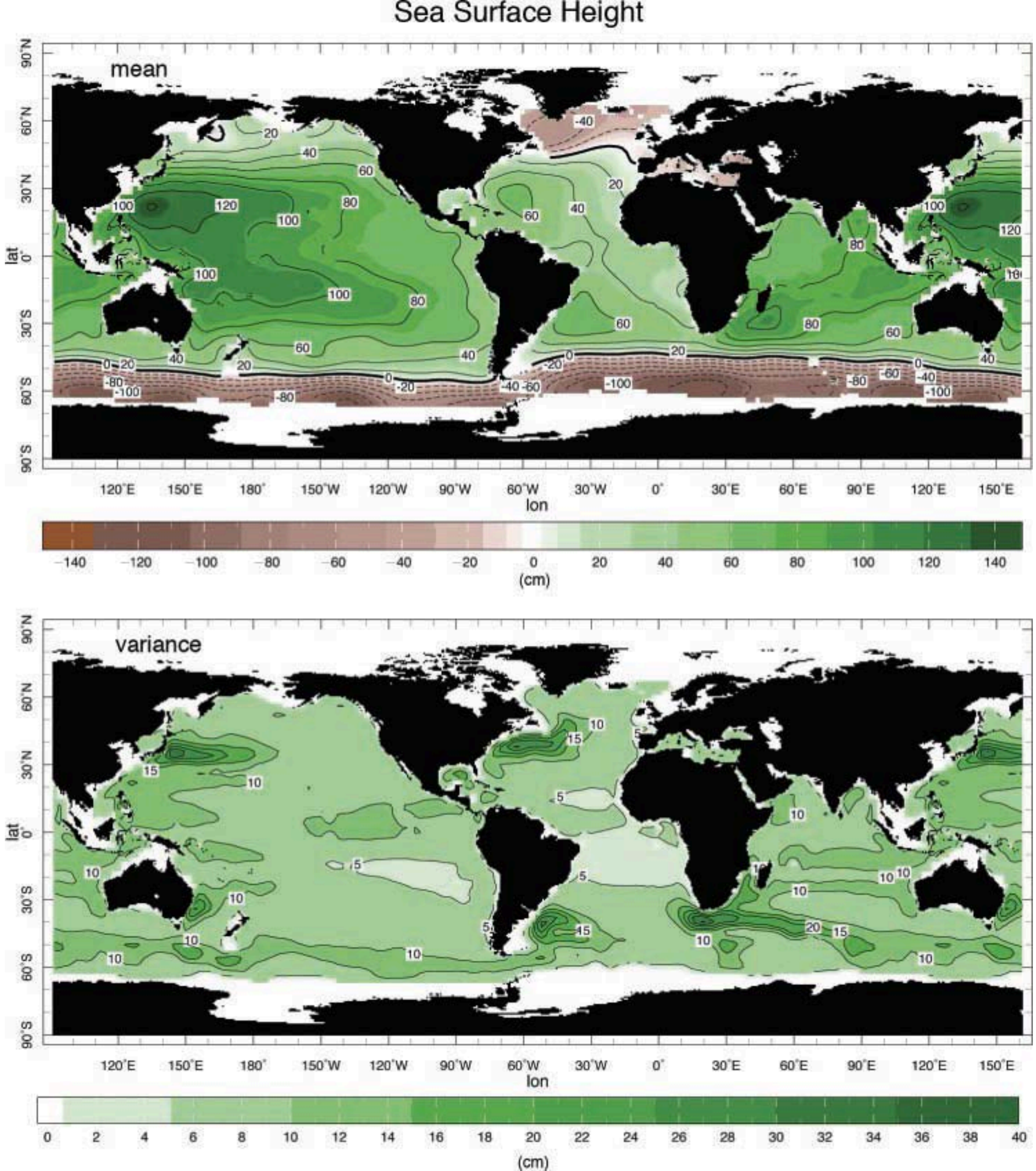

Fast on the west
Subtropical gyre
slow on the east
< 10 cm/s
~ 5 years
10 cm/s
Latitude
Longitude
90°N
60°N
30°N
0°
30°S
60°S
90°S
90°W
60°W
30°W
0°
30°E



Latitude
Longitude
10 cm/s

Currents And Pressure at 700m in The Atlantic




Sea Surface Height
mean
variance
lat
lon
90°N 60°N 30°N 0° 30°S 60°S 90°S
120°E 150°E 180° 150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E
−140 −120 −100 −80 −60 −40 −20 0 20 40 60 80 100 120 140
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
(cm)

Zonal-Average, Annual-Mean, Potential Density (kg/m³)